The use of real-time monitoring during flywheel resistance training programmes: how can we measure eccentric overload? A systematic review and meta-analysis

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ABSTRACT: This systematic review and meta-analysis aimed to analyse the technologies and main training variables used in the literature to monitor flywheel training devices in real time. In addition, as the main research question, we investigated how eccentric overload can be effectively monitored in relation to the training variable, flywheel shaft type device and the moment of inertia selected. The initial search resulted in 11,621 articles that were filtered to twenty-eight and seventeen articles that met the inclusion criteria for the systematic review and meta-analysis, respectively. The main technologies used included force sensors and rotary/linear encoders, mainly to monitor peak or mean force, power or speed. An eccentric overload was not always achieved using flywheel devices. The eccentric overload measurement was related to the main outcome selected. While mean force ($p = 0.011$, ES = -0.84) and mean power ($p < 0.001$, ES = -0.30) favoured the concentric phase, peak power ($p < 0.001$, ES = 0.78) and peak speed ($p < 0.001$, ES = 0.37) favoured the eccentric phase. In addition, the lower moments of inertia (i.e., from 0.01 to 0.2 kg·m^2) and a cylindrical shaft type (i.e., vs conical pulley) showed higher possibilities to achieve eccentric overload. A wide variety of technologies can be used to monitor flywheel devices, but to achieve eccentric overload, a flywheel cylindrical shaft type with low moments of inertia is advised to be used.

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INTRODUCTION

Resistance training (RT) methods traditionally use free weights [1], weight stacks [2], isokinetic dynamometers [3], and/or the athletes' own body mass [4] to induce overload and associated positive adaptations, in relation to muscle strength development. In addition, strength training can be specifically focused on improving the concentric (CON) or eccentric (ECC) phases of the movement [5]. Concentric training is important to enhance acceleration characteristics in some particular sports contexts, such as linear sprinting [6]. However, in other sports (i.e., team sports), where changes of direction frequently occur and the force is applied in multiplanar movements, the use of eccentric training can be beneficial [7]. Furthermore, increasing the athletes' capacity to break the kinetic energy produced during the concentric phase during the eccentric phase can reduce the injury risk [8, 9].

Intensity and volume are two typical training variables that can be modified over time and can also be monitored in real time [10]. Of these variables, the training intensity can mostly determine the chronic adaptations [11]. A minimum training stimulus (i.e., intensity threshold) is necessary to evoke positive adaptations [12]. Hence, objective knowledge of the training intensity is of paramount importance. A typical method to indicate the training intensity in RT is the use of the one-repetition maximum (1-RM) and its relative percentages [13]. Moreover, recent works suggest the use of bar speed to objectively control the training intensity, known as velocity-based training (VBT) [13, 14]. Traditionally, strength exercises have been monitored using force sensors, such as force platforms [15–17] or strain gauges [2], linear encoders [18–20] and, more recently, accelerometers [21]. Although they can be used to describe the exercise performance via mechanical outputs, nowadays, there is increasing interest in their use as biofeedback [13, 14]. Although VBT has gained an increasing audience in recent years, its applications are mainly focused on the CON phase of the exercises.

Considering eccentric training, an interesting paradigm that has been developed over the last 20 years [22] is flywheel training. Compared to free weights, the main difference is related to the influence of gravity on the loading; while free weights are gravity-dependent (isoinertial translational movements on the vertical or other planes), flywheel resistance training devices (FRTD) are gravity independent [23], due to the rotary inertial setting of the exercise (isoinertial rotary movement). Hence, while the 1-RM occurs in traditional training models, in the flywheel paradigm, it is not measurable or achievable. Another interesting characteristic of FRTD is that the shaft type (i.e., vertical cone (VC) or horizontal cylinder (HC)) and its radius [19] determine the final mechanical output, together with the moment of inertia [15, 24]. Surprisingly, only recently has there been increasing interest in characterizing the mechanical overload of different exercises using these devices [15, 19, 24, 25]. As with free weights, the literature shows a mechanical overload when the moment of inertia is increased [15, 26]. However, the different types of FRTD, based on their shaft type, and the absence of 1-RM make it challenging to compare across different RT programmes and exercises. Thus, the provision of accurate mechanical descriptive outputs is of importance to quantify the neuromuscular performance of a given training session using FRTD.

Different mechanical outputs have been reported in the literature when FRTD were used as part of an RT programme. While initial works measured FRTD with force sensors [15, 22, 27], goniometers [23, 28], and electromyography (EMG) [1, 15, 29] to describe the mechanical or neuromuscular loading, nowadays the use of encoders is more common [2, 20, 30]. Consequently, several mechanical variables derived from encoders (i.e., *force*, *power,* or *velocity*) have also been reported in association with FRTD. Of interest, the stretch-shortening cycle (SSC) has recently been quantified, because one of the main characteristics of these devices is the coupled concentric-eccentric actions [23]. Furthermore, FRTD have been widely used with the objective of achieving eccentric overload (EO), also known as enhanced negative work-based training [31]. Typically, EO is achieved if the ECC output is higher compared to the CON output [23, 32]. An early work suggested that a higher EO can be achieved with FRTD compared to free weights [23]. However, the EO is achieved only during small windows or brief episodes of the eccentric movement phase [23, 33]. This is explained by the deliberate delay in the voluntary brake at the end of ECC to achieve a higher mechanical peak, proposed as a technique to achieve the EO [32]. The manoeuvre to elicit EO must be learned by the individual. Nevertheless, the EO does not always occur using FRTD, even when ensuring this learned braking technique [19]. Therefore, it is crucial to determine the extent to which researchers are successful in inducing a real EO, because this can have practical implications for the training routines that incorporate FRTD.

Of note, the term “eccentric overload” appears in the title of several papers related to FRTD [8, 19, 27, 34]. However, EO has not been evidenced in all works using FRTD. Therefore, the purpose of this systematic review with meta-analysis was to characterize the monitoring technologies and related real-time mechanical output during the concentric and/or eccentric movement phases using FRTD. In addition, we propose the following research question: is it possible to achieve an EO (i.e., *force*; *velocity*; *power*) while using FRTD?

MATERIALS AND METHODS

Registry of systematic review protocol

The systematic review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) recommendations [35]. The study protocol was registered at the International Prospective Register of Systematic Reviews (PROSPERO) database (number CRD42020187386).

Search strategy

Original articles published in PubMed, Web of Science, Scopus, and Cochrane electronic databases were searched. The search strategy used a combination of appropriate terms with Boolean operators: flywheel training OR flywheel exercise OR flywheel inertia OR flywheel resistance training OR flywheel resistance exercise OR variable inertial OR rotary inertial OR inertial training OR inertial exercise OR isoinertial training OR isoinertial exercise OR eccentric overload OR eccentric overload training OR enhanced eccentric OR gravity independent. There were no language or year restrictions. The final search was carried out in June 2020. In addition, a complementary search was carried out in the reference lists of pre-selected primary articles and other sources to identify relevant studies which were manually included when applicable [36].

Eligibility criteria and selection process

The studies were considered eligible if they met the following criteria: a) included full-text original papers (reviews, letters, opinions, case reports, and book chapters were excluded); b) full-text manuscripts published in English; c) used an FRTD during exercise; d) used technology which provides mechanical (i.e., *force*, *power* or *velocity*) or muscle activation outputs (i.e. EMG) for the CON and ECC movement phases; e) published in a peer-reviewed journal; f) included only healthy adults as participants (> 18 years); g) used resistance training; and h) described the training intervention with the following specifications: FRTD equipment description, type of exercise, moment of inertia (i.e., external load), volume and training intensity. For meta-analysis purposes, we selected only papers which provided information regarding mean and peak mechanical outputs (i.e. *force* and/or *power* and/or *velocity)* during both CON and ECC movement phases.

The results obtained from the different databases were grouped and duplicates were removed (Figure 1). Two researchers (AM and

PG) screened studies by analysing titles and abstracts. The screening was performed using the Endnote software (v.X9, Thompson Reuters) and the Rayyan online platform [37] (v. 1.0). The full-text analysis of previously selected articles was conducted by both researchers independently based on the inclusion criteria. The discrepancies were analysed by a third researcher (FF). Any remaining disagreements were resolved by a fourth researcher (FN).

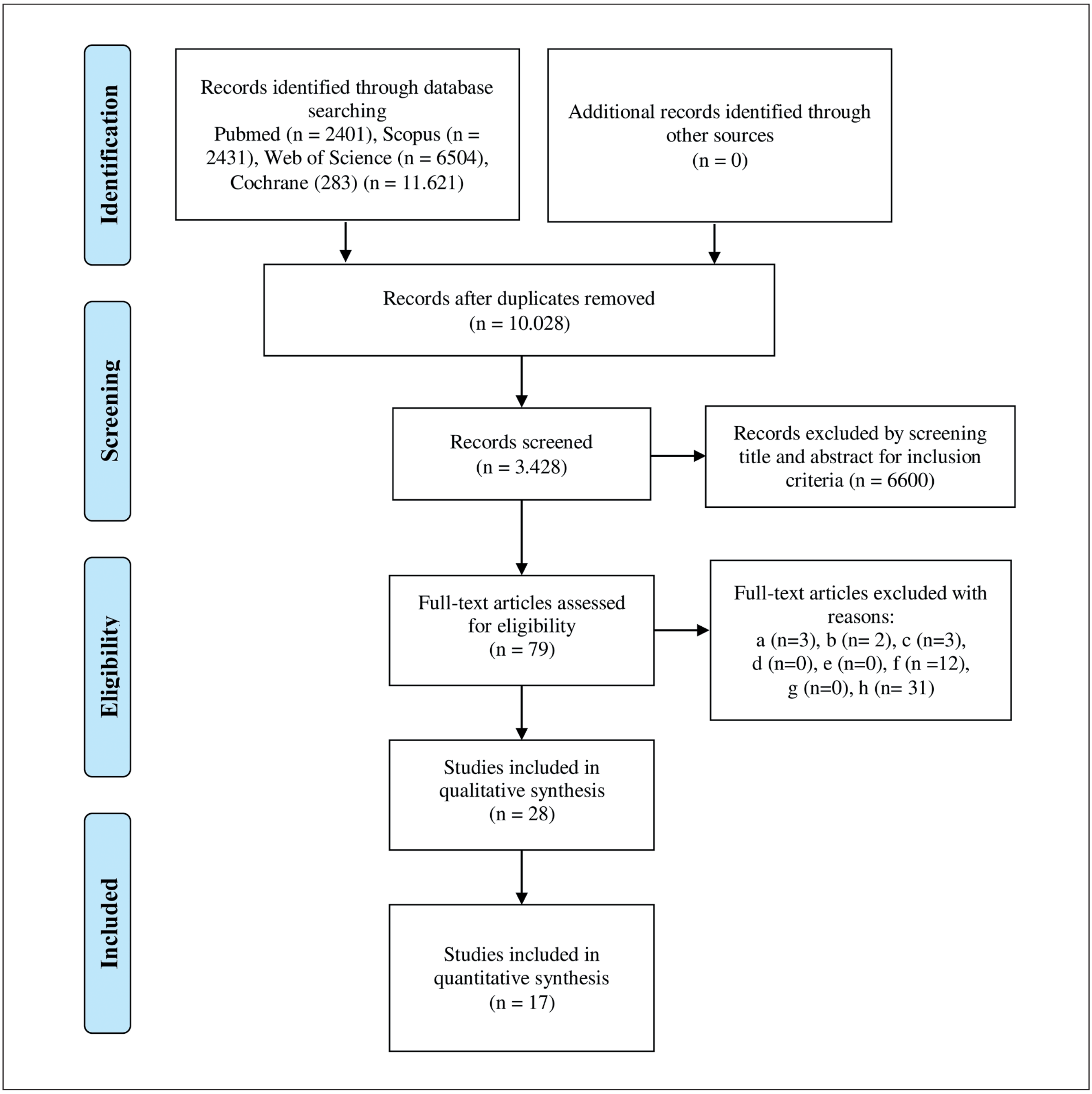


FIG. 1. PRISMA flow diagram of systematic search and studies included. a) included full-text original papers (reviews, letters, opinions, case report, book chapters were excluded); b) full-text manuscripts published in English; c) used an FRTD during exercise; d) used technology which provides mechanical (i.e., force, power or velocity) or muscle activation outputs (i.e., EMG) for the CON and ECC movement phases; e) published in a peer-reviewed journal; f) included only healthy adults as participants (> 18 years); g) used resistance training; and h) described the training intervention with the following specifications: FRTD equipment description, type of exercise, moment of inertia (i.e., external load), volume, and training intensity

Data extraction

Data extraction was performed by three researchers (FF, FN, and AM). Included studies were read to extract the following variables: authors, year of publication, descriptive information of sample, device shaft type, exercise evaluated, assessment device, moment of inertia, volume, real-time mechanical variables monitored, and outcomes evaluated. The mean and standard deviation (SD) values of measures of interest were extracted by two independent researchers (FF and FN). When the data of interest could not be obtained directly from the articles, we contacted the authors to request the information. If no response was obtained, validated ($r = 0.99$, $p < 0.001$) online software (WebPlotDigitizer, v. 4.3, Pacifica, California USA) was used to extract the data from the figures [38]. Two independent researchers (FF and FN) obtained the data using the aforementioned software. Extracted data were analysed by a third researcher (AM).

Methodological quality assessment

The quality of the cross-sectional studies was individually assessed by means of the modified version of the Downs and Black checklist [39]. Fourteen items from the original scale were included in the quality assessment. In addition, item 10 of the original scale asking "Have actual probability values been reported (e.g. 0.035 rather than < 0.05)?" was modified to "Reports sufficient descriptive statistical data rather than just p-values". Items 1–10 refer to "reporting", item 12 refers to "external validity", items 15–25 refer to "internal validity". The quality analysis was conducted by two independent researchers (PG and FN; agreement = 89.5%), and disagreements were resolved through analysis by a third reviewer (AM). We characterized the quality of evidence for each study according to criteria previously used in the literature [40]. The "Quality Index" was obtained by dividing the individual score of each study by 14 and multiplying by 100. Studies with a Quality Index > 66.7% were classified as having low risk of bias, between 50% and 66.6% as having moderate risk of bias, and with < 50% as having high risk of bias.

The risk of bias assessment and quality of evidence of longitudinal studies were evaluated using the Physiotherapy Evidence Database – PEDro scale [41]. The assessment was independently conducted by two researchers (PG and FN; agreement = 87.8%). A third reviewer (AM) was consulted in case of disagreements. Scoring criteria adopted in previous studies were used to analyse the quality of evidence [42]. The studies were considered as being of "excellent" (9–10 points), "good" (6–8 points), "fair" (4–5 points), or "poor" methodological quality (≤ 3 points)[43].

Statistical analysis

Descriptive results are shown as pooled mean ± pooled SD. Although two studies can be used in meta-analyses, considering that reduced sample sizes are common in the sport science literature [44], a meta-analysis for a given flywheel-derived outcome (i.e., *power, force, velocity*) was conducted if at least three studies provided sufficient data for the calculation of effect sizes (ES) [43]. Means and standard deviations (SD) for a measure of flywheel-derived outcomes from the CON and ECC were converted to Hedges' g ES (corrects the typical Cohens' effect size multiplying it by a correction factor to avoid problems with small samples [45] and corrects biases due to sample size differences across study groups). In all analyses, we used the random-effects model to account for differences between studies that might impact the treatment effect [46]. The ES values are presented alongside their respective 95% confidence intervals (CIs). Calculated ES were interpreted using the following scale: < 0.2, trivial; 0.2–0.6, small; > 0.6–1.2, moderate; > 1.2–2.0, large; > 2.0–4.0, very large; > 4.0, extremely large [47]. Heterogeneity was assessed using the I^2 statistic, with values of < 25%, 25–75%, and > 75% considered to represent low, moderate, and high levels of heterogeneity, respectively. The risk of bias was explored using the extended Egger's test [48]. In the case of a significant Egger's test result, correction procedures (i.e., trim and fill method) were performed. In addition to the main analyses, we used the flywheel shaft type and flywheel inertia as moderators to explore their influence on the results. Specifically, shaft type was divided into VC and HC, while inertia ($kg \cdot m^2$) was grouped into four categories: 0.01 to 0.1, 0.1 to 0.2, 0.2 to 0.3, and 0.3 to 0.4. We have created those categories according to simple and easy thresholds which include all the moments of inertia used in the literature, to our knowledge. All analyses were carried out using the Comprehensive Meta-Analysis program (v. 2; Biostat, Englewood, NJ, USA). The statistical significance threshold was set at $p < 0.05$.

RESULTS

Search results

The database search yielded a total of 11,621 potential studies (Figure 1). Twenty-eight studies were included in the systematic review (qualitative synthesis) [1, 2, 24–30, 33, 49, 50, 3, 51–58, 16–20, 22, 23], and seventeen were included in the meta-analysis (quantitative synthesis) [2, 17, 51, 53–58, 19, 20, 24–27, 30, 50]. Most of the papers were not included in the meta-analysis because they did not provide specific information about the moment of inertia used [3, 16, 18, 22, 23, 33, 49]. In addition, two studies [25, 28] did not provide data from both CON and ECC movement phases. Finally, two studies [1, 29] were excluded because they only monitored EMG.

Study characteristics

The study characteristics are shown in Table 1. The majority of the studies (n = 19) included male or female physically active subjects [1, 2, 29, 30, 49–53, 56–58, 3, 16, 19, 22, 23, 25–27]. The rest of the studies (n = 8) used team sports athletes [18, 20, 24, 28, 50, 54], resistance training naive participants [55], and national level sprinters [17]. The most frequently used flywheel shaft-type device was HC (n = 21) [1, 2, 28–30, 49–51, 54, 56–58, 19, 20, 22–27], while the VC type was less frequently used (n = 6) [16–19, 52, 53]. Most of

TABLE 1. Description of the flywheel devices, monitoring technologies, real-time mechanical variables and training outcomes

Study	TS	Sample	ST	Exercise	Assessment device	MI (kg · m^2)	Volume per exercise (F/S/R)	Real time variables measured	CON	ECC
Aagaard et al. [28]	A	21 elite soccer players	HC	Single-leg extension	Strain gauge, Dynamometer	Unclear	1 session x 1 week / 4 x 16	Peak speed, Peak torque, Peak power, Torque Power at 50% of CON	Yes	No
Berg & Tesch [32]	A	11 physically active men	HC	Leg press	Strain gauge, Linear potentiometer, EMG	?	1 session x 1 week / 1 x 10	Mean force, Peak force, Momentary speed, Mean Power, Mean Work, EMG	Yes	Yes
Tesch et al. [23]	C	10 physically active subjects (men = 7 and women = 3)	HC	Single-leg extension	Strain gauge	?	2–3 session x 5 weeks / 4 x 7	Mean force, Peak power	Yes	Yes
Caruso et al [49]	A	31 physically active subjects (men = 13 and women = 18)	HC	Calf press	Force platform, EMG	?	1 session x 1 week / 3 x 10	Mean work, Mean power, EMG	Yes	Yes
Chiu & Salem [16]	A	11physically active (men = 5 and women = 6	VC	Lunge, Front squat, Push press	Force platform, 8-camera optoelectronic motion capture system	?	1 session x 1 week / 3 x 3	Net joint impulse, Net join moment, Net joint power, Relative impulse	Yes	Yes
Pozzo et al. [33]	A	9 physically active men	HC	Single-leg extension	Strain gauge, Potentiometer,	?	2 sessions x 1 week / 1 x 30	Momentary torque, EMG, CV, iMNF, ARV	Yes	Yes
Tous-Fajardo et al. [50]	A	20 male soccer/rugby players	HC	Leg curl	Strain gauge, linear encoder, EMG	0.11, 0.22	1 session / 1 x 6	Peak force Mean force, Peak power, Mean power, Peak speed, Mean speed, EMGrms, EMG-E:C-r	Yes	Yes
Norrbrand et al. [27]	C	15 physically active men	HC	Single-leg extension	Strain gauge, Linear encoder	0.11	2–3 session x 5 weeks / 4 x 7	Mean speed, Total work, Peak power, Mean power, Peak force, Mean force,	Yes	Yes
Norrbrand et al. [1]	C	9 physically active men	HC	Single-leg extension	EMG	0.11	2–3 session x 5 weeks / 4 x 7	Normalized EMG, EMGrms	Yes	Yes
Norrbrand et al. [51]	A	10 trained men	HC	Leg press	Strain gauge, Linear encoder, EMG	0.14	1 session / 5 x 10	Peak force, Mean force, Normalized EMG	Yes	Yes
Carmona et al. [52]	A	10 physically active men	VC	Half-squat	Strain gauge and linear encoder	Minimum cone radius	1 session / 7 x 10	Momentary speed, Momentary force, Peak power, Mean power,	Yes	Yes
Fernandez-Gonzalo et al. [2]	C	32 physically active subjects (men = 16, women = 16)	HC	Leg press	Encoder	0.14	2–3 sessions x 6 weeks / 4 x 7	Peak power, Mean power, EO (%)	Yes	Yes
Coratella et al. [3]	A	13 physically active men	-	Squat	Encoder	?	2 sessions / 10 x 10	Peak power, Mean power	Yes	Yes

TABLE 1. Continue

Study	TS	Sample	ST	Exercise	Assessment device	MI (kg · m^2)	Volume per exercise (F/S/R)	Real time variables measured	CON	ECC
Moras et al. [53]	A	21 physically active men	VC	Squat	Strain gauge, Linear encoder	0.27	1 session / 6 x 6	Peak force, Mean force, Mean speed	Yes	Yes
Vázquez-Guerrero et al. [17]	A	13 male national-level sprinters	VC	Squat	Strain gauge	0.12, 0.27	1 session / 4 x 3	Peak force, Mean force	Yes	Yes
Martinez-Aranda et al. [26]	A	22 physically active subjects (men = 11 and women = 11)	HC	Single-leg extension	Strain gauge, Rotary encoder,	0.0125, 0.025, 0.0375, 0.05, 0.075, 0.1	1 session / 6 x 3	Peak force, Mean force, Coupling CON-ECC time, SSC, Momentary torque, Power (only CON) Work (only CON) EO	Yes	Yes
Nuñez et al. [18]	A	15 rugby players	VC	High Pull	Linear encoder, Force platform	Maximal cone radius	2 sessions / 6 x 6	Peak speed, Peak acceleration, Mean propulsive speed, Mean propulsive acceleration, Mean force, Peak force	Yes	Yes
Sabido et al. [54]	C	18 handball players	HC	Half-squat, Lunge	Rotary encoder	0.05	1 session x 7 weeks / 2 x 8 per exercise	Mean Power, Peak Power	Yes	Yes
Illera-Domínguez et al. [55]	C	10 young resistance training naive	HC	Squat	Friction encoder	0.09	2–3 sessions x 4 weeks / 5 x 10	Mean force, Mean power	Yes	Yes
Sabido et al. [24]	A	24 high-level handball players	HC	Quarter-squat	Rotary encoder	0.025, 0.050, 0.075, 0.100	1 session x 4 weeks / days of 4x10 + 1x15 per load	Peak power, E:C-r	Yes	Yes
Alkner et al. [29]	A	8 physically active men	HC	Leg press	Strain gauge, EMG	0.1105	1 session / 1 x 8	EMG	Yes	Yes
Carroll et al. [15]	A	17 physically active subjects (men = 16, women = 1)	HC	Squat	Force plateforms, EMG	0.01, 0.025, 0.050, 0.060 0.075 0.1	1 session / 2 x 13 + 1 session / 1 x 13	Peak force, Peak velocity EMG	Yes	Yes
Castillo et al. [57]	A	24 physically active men	HC	Half-squat	Rotary encoder	0.025, 0.05, 0.075, 0.1	2 sessions x 1 week / 4 x 8	Peak power, Mean power	Yes	Yes
Maroto-Izquierdo et al. [58]	C	10 physically active men	HC	Single-leg squat	Rotary encoder	0.05	2 sessions x 6 weeks / 5 x 3	Peak power	Yes	Yes
Piqueras-Sanchiz et al. [30]	A	20 physically active men (10 per load)	HC	Lunge	Rotary encoder	0.075, 0.1	1 session x 1 week / 4 x 7	Peak power, Mean power, Mean speed	Yes	Yes
Núñez et al. [19]	A	22 physically active men	HC VC	Half-squat	Force platforms, Linear encoder	0.11, 0.22, 0.33	2 session x 1 week / 3 x 7	Peak force, Peak speed, Mean force, Impulse	Yes	Yes

TABLE 1. Continue

Study	TS	Sample	ST	Exercise	Assessment device	MI (kg · m^2)	Volume per exercise (F/S/R)	Real time variables measured	CON	ECC
Raya-Gonzalez et al. [20]	A	20 young elite soccer players (U17)	HC	Half-squat Lateral squat	Rotary encoder	0.025 (Half-squat), 0.01 (Lateral squat)	2 session x 1 week / 2 x 6 (per exercise)	Mean power, Peak power	Yes	Yes
Worcester et al. [25]	A	9 physically active subjects (male = 3; female = 6)	HC	Squat	Rotary encoder	0.05, 0.075, 0.1	1 session x 1 week / 3 x 6	Mean power, Mean force, Mean speed,	Yes	Yes

Note: HC: horizontal cylinder; VC: vertical cone; E:C-r = eccentric:concentric ratio; EO: eccentric overload; CV: conduction velocity; iMNF: instantaneous mean power spectral frequency; ARV: mean rectified value; F/S/R: frequency / sets / repetitions; D: study; CON: concentric; ECC: eccentric; EMG: electromyography; EMGrms: electromyography root mean square; SSC: stretch-shortening cycle; ? = data not provided by authors; MI = moment of inertia.

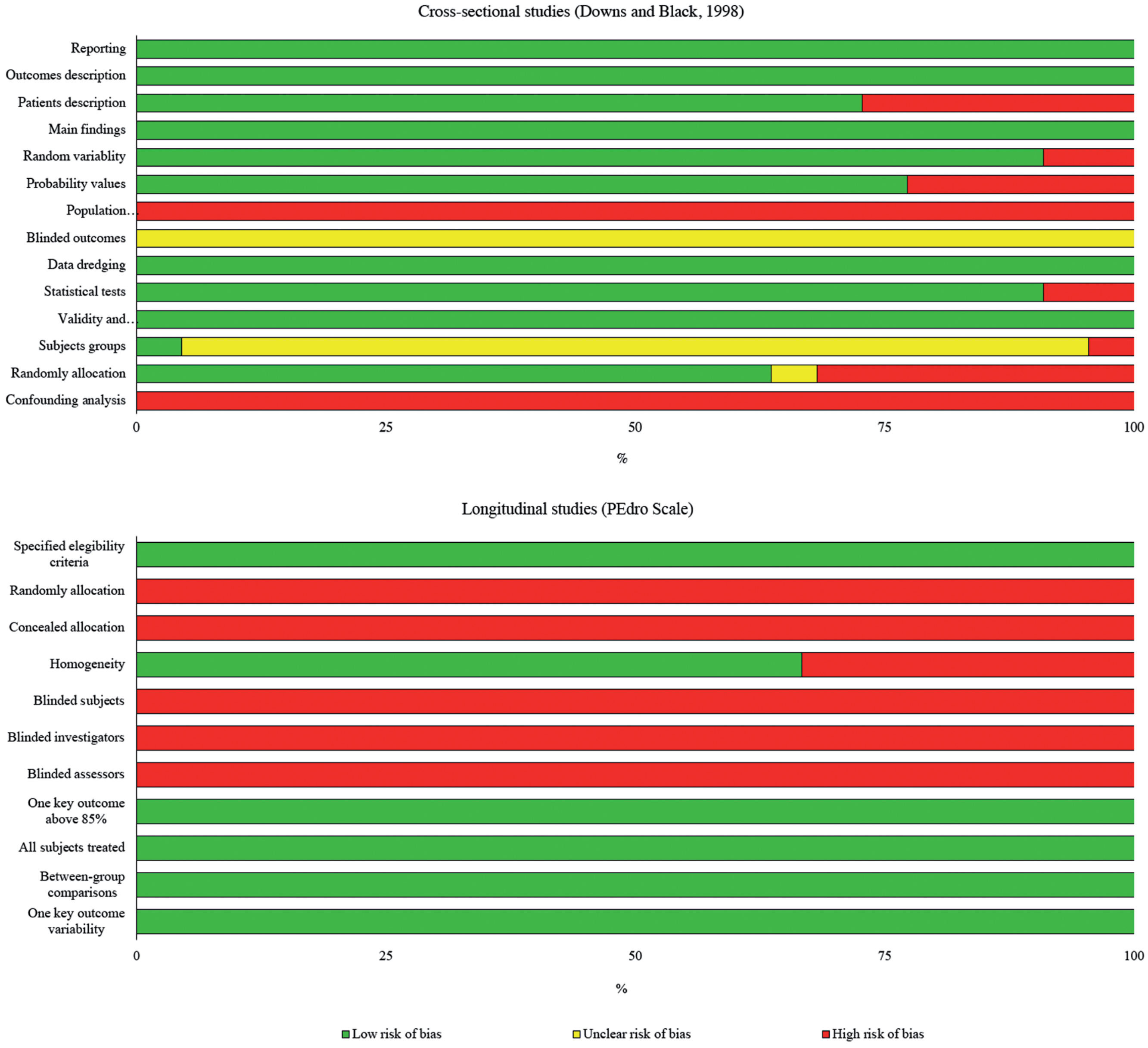


FIG. 2. Summarized risk of bias for cross-sectional (upper figure) and longitudinal studies (lower figure).

TABLE 2. Pooled mechanical outcomes summary for each exercise, flywheel resistance training device (FRTD) shaft-type, moment of inertia and movement phase.

Exercise	FRTD	Inertia group	Mean Force (N)		Peak Force (N)		Mean Power (w)		Peak Power (w)		Mean velocity (m/s^1 or turns/s^2 or °/s^3)		Peak velocity (m/s)	
			CON	ECC	CON	ECC	CON	ECC	CON	ECC	CON	ECC	CON	ECC
Half-squat	HC	0.01 to 0.1	-	-	-	-	599.96 ± 151.38	535.83 ± 141.83	1011.84 ± 151.38	955.75 ± 235.60	-	-	-	-
Half-squat	HC	0.1 to 0.2	1835.54 ± 321.82	1693.97 ± 344.04	2453.00 ± 426.22	2337.09 ± 467.54	597.30 ± 178.16	579.39 ± 179.92	1095.07 ± 178.16	1215.10 ± 363.14	-	-	0.57 ± 0.09	0.57 ± 0.10
Half-squat	HC	0.2 to 0.3	1919.15 ± 364.65	1786.47 ± 363.72	2516.16 ± 465.42	2371.03 ± 476.52	-	-	-	-	-	-	0.44 ± 0.06	0.46 ± 0.05
Half-squat	HC	0.3 to 0.4	1915.37 ± 37933	1802.22 ± 399.63	2508.04 ± 513.48	2382.62 ± 565.22	-	-	-	-	-	-	0.35 ± 0.05	0.37 ± 0.08
Half-squat	VC	0.1 to 0.2	1601.11 ± 262.07	1340.45 ± 223.57	2290.74 ± 426.92	2000.48 ± 434.38	-	-	-	-	-	-	0.92 ± 0.16	0.87 ± 0.09
Half-squat	VC	0.2 to 0.3	1702.73 ± 257.16	1430.24 ± 238.12	2376.31 ± 349.55	2035.3 ± 378.52	-	-	-	-	-	-	0.88 ± 0.13	0.86 ± 0.06
Half-squat	VC	0.3 to 0.4	1763.33 ± 271.07	1460.9 ± 258.83	2398.78 ± 369.43	2038.75 ± 377.60	-	-	-	-	-	-	0.79 ± 0.12	0.77 ± 0.16
Lateral-squat	HC	0.01 to 0.1	-	-	-	-	255.25 ± 86.24	210.31 ± 75.04	438.70 ± 154.05	473.13 ± 164.37	-	-	-	-
Leg curl	HC	0.1 to 0.2	499.00 ± .74.00	230.00 ± 50.00	643.50 ± 69.50	635.00 ± 73.00	171.00 ± 29.5	60.5 ± 21.50	278.00 ± 54.00	203.50 ± 48.50	0.34 ± 0.02^1	0.39 ± 0.06^1	0.52 ± 0.05	0.67 ± 0.06
Leg curl	HC	0.2 to 0.3	518.00 ± 87.00	331.50 ± 48.00	791.00 ± 123.00	824.50 ± 145.00	146.50 ± 37.50	74.5 ± 23.50	242.50 ± 68.00	222.00 ± 69.00	0.28 ± 0.02^1	0.03 ± 0.03^1	0.43 ± 0.06	0.52 ± 0.08
Leg press	HC	0.1 to 0.2	1546.00 ± 385.00	1325.00 ± 269.00	2172.00 ± 385.00	2146.00 ± 262.00	375.23 ± 99.09	390.36 ± 100.93	542.00 ± 148.00	552.00 ± 116.00	-	-	-	-
Lunge	HC	0.1 to 0.2	-	-	-	-	572.33 ± 148.00	529.16 ± 131.83	804.00 ± 124.88	1016.20 ± 177.28	-	-	-	-
Quarter-squat	HC	0.01 to 0.1	-	-	-	-	-	-	1370.25 ± 290.50	1378.75 ± 371.25	-	-	-	-
Quarter-squat	HC	0.1 to 0.2	-	-	-	-	-	-	1107.66 ± 240.75	1238.08 ± 278.83	-	-	-	-
Single-leg extension	HC	0.01 to 0.1	93.36 ± 22.27	115.36 ± 25.30	140.27 ± 30.93	167.60 ± 37.27	-	-	-	-	-	-	-	-
Single-leg extension	HC	0.1 to 0.2	223.60 ± 48.36	242.32 ± 61.98	314.90 ± 56.22	314.13 ± 57.35	-	-	325.00 ± 91.00	326.50 ± 91.00	115.25 ± 5.50^2	117.5 ± 8.75^2	-	-
Single-leg kick extension	HC	0.1 to 0.2	-	-	-	-	111.51 ± 23.08	93.82 ± 18.96	195.60 ± 41.25	172.55 ± 34.50	6.73 ± 0.49^3	6.56 ± 0.58^3	-	-
Squat	HC	0.1 to 0.2	2279.87 ± 383.87	2331.73 ± 374.73	-	-	618.42 ± 174.36	639.47 ± 251.34	-	-	-	-	-	-
Squat	VC	0.1 to 0.2	1819.83 ± 258.23	1595.97 ± 190.16	2864.80 ± 837.20	2950.00 ± 872.00	-	-	-	-	-	-	-	-
Squat	VC	0.3 to 0.4	1668.82 ± 236.50	1371.97 ± 188.95	2371.37 ± 748.70	2441.43 ± 886.27	-	-	-	-	0.67 ± 0.09^1	0.69 ± 0.07^1	-	-

the studies were designed as cross-sectional interventions (n = 21), using one or two sessions with variations in training volume from 1 to 10 sets with 6 to 30 repetitions each. The longitudinal studies (n = 7) included training interventions of between 4 and 7 weeks, with two or three training sessions per week.

The studies showed different purposes when resistance flywheel devices were used. The first published flywheel research were focused on mechanical and electrical muscle activity when using those devices [22, 23, 28, 33, 49–51]. In relation, other research studied the physiological and muscle structure effects [2, 27, 30, 55] and, more recently, the mechanical output characterization [17, 19, 25, 53] including progressive resistance testing [15, 24, 26]. Also, some research compared the flywheel resistance training devices with other training equipment [16, 29, 58–60]. Finally, some works focused on using these devices in training programmes and performance development [20, 54, 57].

Risk of bias assessment

The results of the risk of bias assessment with the Downs and Black scale and PEDro scale are included as supplementary material (Figure 2). For cross-sectional studies (Downs and Black scale), the average scores ranged from 6 to 9 from a total of 14. Overall, 41% of the cross-sectional studies were graded as having a low risk of bias (n = 9), 55% were classified as having moderate risk of bias (n = 12), and 4% as having high risk of bias (n = 1). No study included subjects who were prepared to participate as a representative of the entire population (Item 12) or made adjustments for confounding variables (Item 25). For longitudinal studies (PEDro scale), the average score from the 6 included studies ranged from 5 to 6 out of a maximum of 10. That is, 66.7% were classified as being good (n = 4) and 33.3% as moderate methodological quality (n = 2). None of the included studies were classified as excellent or poor quality.

Monitoring technologies and main training outcomes

The monitoring technologies and main training outcomes are shown in Table 1. A wide range of moments of inertia was used, from 0.01 kg·m^2 using an HC device [20, 56] to 0.33 using a VCor HC device [19]. The moments of inertia used with VC devices were usually higher compared to HC devices. The most frequent training outcomes were related to *force* [3, 16, 33, 49–53, 56, 17–19, 22, 23, 27–29], *power* [2, 22, 55, 58, 23, 24, 27, 28, 30, 50, 52, 54], and *velocity* [19, 20, 53–55, 57, 58, 60, 24–27, 30, 50–52]. EMG was also measured in real time [1, 15, 22, 29, 49–51]. Some studies included the use of the E:C-r [24, 50, 61] or similar outcomes [2, 26] to measure the EO. To measure *force* in real-time, the majority of the studies used strain gauges or force platforms. The studies that monitored *velocity* used linear [19, 27, 50, 51, 53, 60], friction [55], or rotary encoders [20, 24–26, 30, 54, 57, 58]. *Power* was calculated using strain gauges, force platforms, linear, friction, or rotary encoders, or was directly measured using a potentiometer.

Mechanical outputs

Descriptive variables for each exercise, FRTD shaft type, and inertia group are included as supplementary material. The highest mean and peak force values were obtained with the squat exercise and its variants, while the lowest were observed with the single-leg extension exercise. The same was observed with the mean and peak power values. These patterns occur regardless of analysing the CON or ECC movement phases of the exercise. There was a systematic increase in mean and peak force as the moment of inertia increased in all exercises and FRTD shaft types, except for the squat exercise when the VC was used, where greater values of mean and peak force were observed with the use of relatively low (0.1 to 0.2 kg·m^2) moments of inertia. In addition, the use of lower moments of inertia tended to produce greater mean and peak power (Table 2).

Group by Outcome	Statistics for each study						
	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Mean force	-0.507	0.189	0.036	-0.877	-0.136	-2.681	0.007
Mean power	-0.117	0.056	0.003	-0.227	-0.007	-2.085	0.037
Mean velocity	0.194	0.147	0.021	-0.093	0.481	1.322	0.186
Peak force	-0.085	0.109	0.012	-0.298	0.128	-0.783	0.434
Peak power	0.529	0.106	0.011	0.322	0.736	5.013	0.000
Peak velocity	0.525	0.203	0.041	0.127	0.922	2.587	0.010

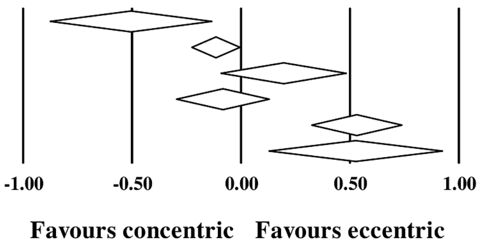


FIG. 3. Pooled effect sizes (white diamonds) for each main outcome comparing the concentric and the eccentric phases of the movement.

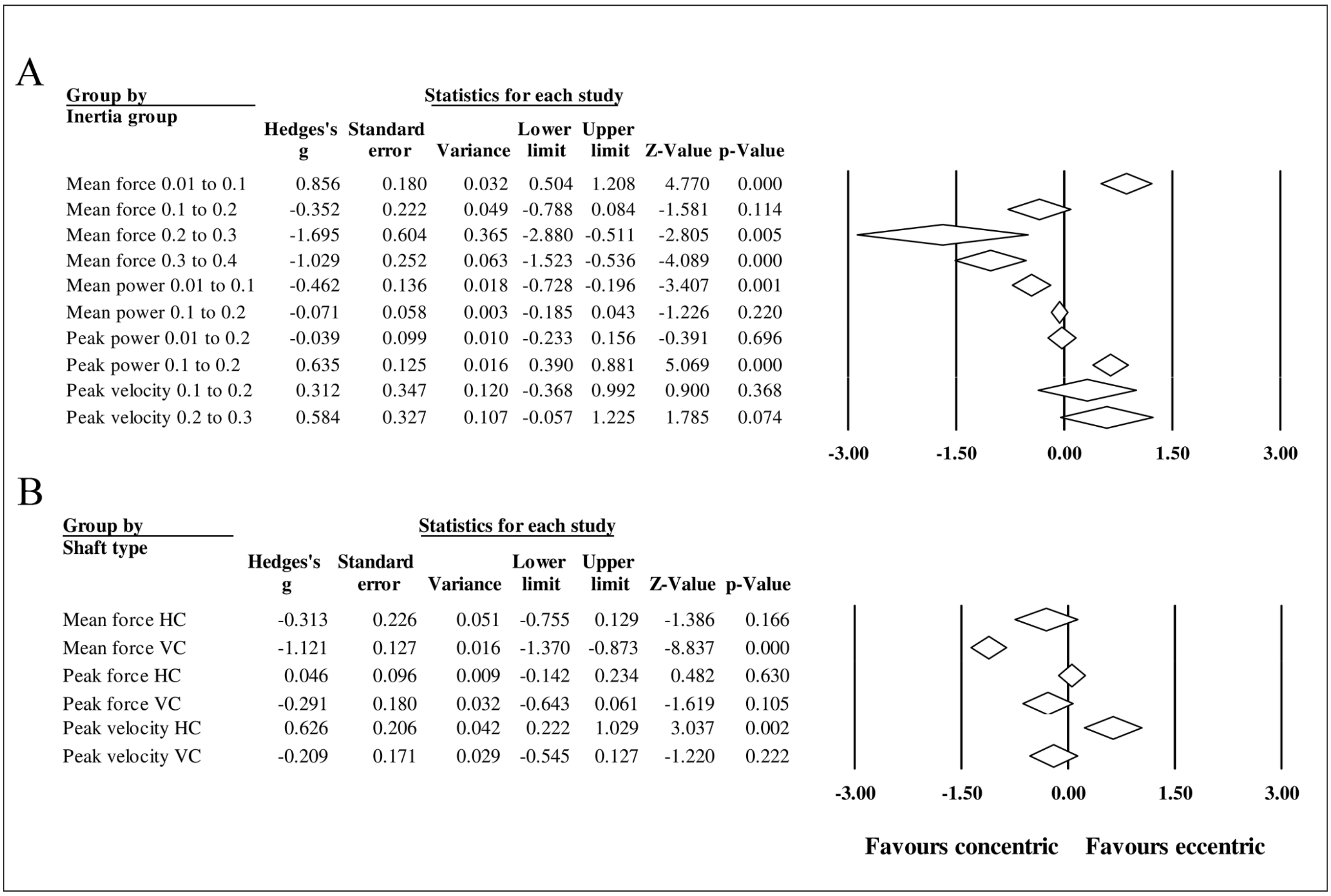
Eccentric overload

Figure 3 shows the main outcomes pooled effect sizes analyses. Individual information for each study, in relation to each training outcome, is included as supplementary material. There was a significant difference in favour of CON compared to ECC in mean force (8 studies, pooled n = 557; trimmed ES = -0.84 – moderate; I^2 = 88.7%; Egger's test p = 0.011) and in mean power (7 studies, pooled n = 1,688; trimmed ES = -0.30 – small; I^2 = 69.1%; Egger's test $p < 0.001$). In contrast, there was a significant difference in favour of ECC compared to CON in peak power (9 studies, pooled n = 1,226; trimmed ES = 0.78 – moderate; I^2 = 83.2%; Egger's test $p < 0.001$) and in peak velocity (2 studies, pooled n = 212; trimmed ES = 0.37 – small; I^2 = 72.3%; Egger's test $p < 0.001$).

The moment of inertia sub-group analyses for each main outcome are shown in Figure 4.A. There were significant differences ($p < 0.001$) in mean force (ES = 0.86 – moderate) and peak force (ES = 0.78 – moderate), favouring ECC, when the lowest range or inertias (0.01 to 0.1 kg·m^2) were used. Peak power also showed a significantly ($p < 0.010$) higher ECC outcome when the range between 0.1 and 0.2 kg·m^2 was used (ES = 0.64 – moderate). This range also favoured CON, but only in mean power (ES = -0.46 – small). In contrast, higher moments of inertia significantly favoured CON compared to ECC ($p < 0.001$) in mean force (0.2 to 0.3 kg·m^2 ES = -1.70 – large; 0.3 to 0.4 kg·m^2 ES = -1.03 – moderate). Figure 4.B shows the shaft type devices sub-group analyses for each main outcome. The VC device showed a significantly higher (p = 0.002) CON main force compared to ECC main force (ES = -1.12 – moderate). In contrast, peak velocity showed that an HC device had significantly higher (p = 0.002) ECC compared to CON (ES = 0.63 – moderate).

DISCUSSION

The purpose of this systematic review with meta-analysis was to provide information in relation to the technologies and related real-time mechanical outputs used, when FRTD are implemented during RT programmes for healthy adults. In addition, we wanted to show how to effectively achieve and monitor EO using these devices. We found that 1) not all the studies achieve or prove achievement of EO, although they use this approach as a training objective, 2) the EO



Group by Inertia group	Statistics for each study						
	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Mean force 0.01 to 0.1	0.856	0.180	0.032	0.504	1.208	4.770	0.000
Mean force 0.1 to 0.2	-0.352	0.222	0.049	-0.788	0.084	-1.581	0.114
Mean force 0.2 to 0.3	-1.695	0.604	0.365	-2.880	-0.511	-2.805	0.005
Mean force 0.3 to 0.4	-1.029	0.252	0.063	-1.523	-0.536	-4.089	0.000
Mean power 0.01 to 0.1	-0.462	0.136	0.018	-0.728	-0.196	-3.407	0.001
Mean power 0.1 to 0.2	-0.071	0.058	0.003	-0.185	0.043	-1.226	0.220
Peak power 0.01 to 0.2	-0.039	0.099	0.010	-0.233	0.156	-0.391	0.696
Peak power 0.1 to 0.2	0.635	0.125	0.016	0.390	0.881	5.069	0.000
Peak velocity 0.1 to 0.2	0.312	0.347	0.120	-0.368	0.992	0.900	0.368
Peak velocity 0.2 to 0.3	0.584	0.327	0.107	-0.057	1.225	1.785	0.074

Group by Shaft type	Statistics for each study						
	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Mean force HC	-0.313	0.226	0.051	-0.755	0.129	-1.386	0.166
Mean force VC	-1.121	0.127	0.016	-1.370	-0.873	-8.837	0.000
Peak force HC	0.046	0.096	0.009	-0.142	0.234	0.482	0.630
Peak force VC	-0.291	0.180	0.032	-0.643	0.061	-1.619	0.105
Peak velocity HC	0.626	0.206	0.042	0.222	1.029	3.037	0.002
Peak velocity VC	-0.209	0.171	0.029	-0.545	0.127	-1.220	0.222

FIG. 4. Pooled effect sizes (white diamonds) for each main outcome comparing the concentric and the eccentric phases of the movement, for each sub-group division in relation to the moment of inertia (A) and the flywheel shaft type (B).

was primarily shown when peak power or peak velocity outcomes were measured, and 3) lower moments of inertia (i.e. 0.01 to 0.2 kg·m^2) are more suitable to achieve an EO, especially when an HC shaft type flywheel device was used.

Real-time feedback monitoring

While *velocity* (mean, mean propulsive, or peak [62]) is the most common training outcome used for real-time feedback, our results showed that *velocity* is not so frequently used in FRTD. In contrast, *force* or *power* variables are usually monitored (Table 1). Therefore, external force sensors can be used to monitor mean or peak force in these devices. One of the main interests of using force sensors in FRTD is to understand the resistance that they produce [22]. This opens the door to understand the physical demands (i.e., intensity) of FRTD compared to other equipment [22]. In this line, some studies have measured force in FRTD during RT exercises [22, 51, 56], including comparisons with other training devices [16–18, 29] or to know the moment of torque exerted at a specific range of motion during the exercise [23, 28, 50]. In addition, *force* has been used to gauge the chronic adaptations after a training period [2].

In addition, some authors used *power* to quantify the effects of a training programme [2, 23, 27, 54, 55, 57, 58]. Also, Carmona et al. [52] measured *power* in real time to establish the external load during a training intervention. This is a typical approach in some chronic studies that have monitored *power* in FRTD [3, 63, 64], using the moment of inertia at which the individual generates the maximum power out of the load spectrum [64], also known as optimal training intensity [4].

Finally, it is of scientific and practical interest to monitor *force* [19, 29, 50, 52, 53] or *power* [2, 3, 58, 20, 24, 27, 49, 50, 54, 55, 57] to analyse the EO. More recently, a few works [24, 61] calculated the eccentric-concentric ratio (E:C-r) as an EO indicator. Recently, Martinez-Aranda [26] added the calculation of the SSC, which is a typical characteristic of the FRTD [22]. Interestingly, Nuñez et al. [61] reported that although no EO was achieved using FRTD (E:C-r < 1), the group which used an FRTD increased that ratio. These indices (i.e., E:C-r or SSC) are presented as interesting options to calculate the EO or the eccentric character of the movement.

Mechanical outputs

We found that there is a lack of descriptive information in relation to the kinetic and kinematic demands of different RT exercises performed using FRTD. Our results provide typical mechanical outputs related to addressing this issue (see supplementary materials). Recently, a study by Nuñez et al. [19] showed that the FRTD shaft type determines the real resistance offered. Indeed, the authors found that *impulse*, calculated from *force* and *time*, was the only variable differing between each moment of inertia elicited by different shaft type devices. Actually, Sjöberg et al. [65] observed that the *force* vector direction (i.e., horizontal or vertical) could influence the mechanical output. What is more, the flywheel shaft shape and its radius can determine the real intensity of the exercise, not only the moment of inertia [19].

Eccentric overload

EO was first described in a paper which used an FRTD in 1998 [32]. Since then, many authors have used FRTD in RT programmes, and most of them acknowledged the EO as a mechanical advantage of using these devices with regards to training adaptation. Our results demonstrated that from the original 79 papers which used an FRTD device, only 17 provided enough data to determine the existence (or not) of EO. As we mentioned before, different mechanical outputs were used to determine the existence of EO. Our meta-analysis results support that, combining all the moments of inertia and FRTD shaft types, only peak power (moderate difference) and peak velocity (small difference) demonstrated evidence of EO. In contrast, mean force (moderate difference) and mean power (small difference) showed the opposite trend (higher CON output). Hence, the mechanical output selected can differently reveal or not the existence of an EO. There are a few possible explanations for these results. First, as acknowledged by Berg & Tesch [32], the EO may occur when participants are instructed not to resist immediately after completion of the concentric action, thus braking toward the end of the eccentric phase to stop the movement. Thus, individuals must have the ability to reduce the amount of energy accumulated during CON. Indeed, Tous et al. [50] demonstrated that experience is an important factor in relation to achieving EO. With training experience, at least the ECC phase can be improved (i.e., higher E:C-r) [61]. Moreover, gender can also have an influence [2]. Furthermore, Nuñez et al. [19] suggested that the kind of exercise (i.e., open or closed chain) might also determine the possibilities of achieving EO. Finally, the last explanation is related to the flywheel paradigm. The function of FRTD is based on spinning a flywheel, which is tethered to a rope or strap, which the practitioner pulls to generate kinetic energy during CON [23]. Immediately at the end of CON, the ECC starts and the same amount of energy (at most) is transferred, but in the opposite direction. Hence, higher energy cannot be created during ECC.

Traditional RT programmes have used a higher external load (i.e., % 1-RM) [66, 67] or a higher time under tension during ECC compared to CON [68] to achieve EO. In the first scenario, higher kinetic energy is imposed during ECC due to the increase in the total external load, a fact that is impossible to achieve in FRTD. In the second scenario, the duration of the ECC is higher, thus increasing the tension that muscle fibres must sustain [69]. This has been highlighted as an interesting option for injury prevention purposes [9]. However, in FRTD, as previously shown, instead of increasing the duration of the ECC phase, to achieve EO, the opposite should be performed. In our opinion, this is a possible explanation for the fact that EO can only be achieved by using peak power or peak velocity. Concerning the fact that peak force did not show EO, Alkner et al. [29] suggested that muscles are at rest during ECC, but are working maximally in CON, at least in greater knee angles where higher forces can be developed in a leg press device, for example. In agreement, if to achieve EO, the kinetic energy must be reduced at the last third of the movement, sometimes, a biomechanical disadvantage will exist related to muscle levers, explaining why our results did not show an EO in peak force. Other possible reasons why EO is not achieved in peak force are related to the explanations above, and also to the exercise direction of vector [65]. Consequently, although many authors have used FRTD with EO purposes, we found that many of them did not prove that EO was achieved and, in some cases, it was not. However, many studies that measured muscle EMG showed higher ECC activation when using FRTD [1, 22, 29, 49–51, 70]. Hence, FRTD offer higher ECC activation, even at high velocities [15], compared to other training equipment [1].

Interestingly, Carroll et al. [56] found that although the CON muscle electrical activation increased with the progressive overloading in FRTD, the opposite pattern was found in ECC muscle activation. In addition, kinetic and kinematic overloading is observed when progressive testing is performed in FRTD [15, 24, 25]. These results show a possible influence of the moment of inertia on EO. Accordingly, our results demonstrated that the moment of inertia determined the EO, even in peak force, where an EO was not observed when all shaft types and moments of inertia where considered. Furthermore, mean force also showed a moderate EO in the 0.01 to 0.1 kg·m^2 sub-group, but a large overload in CON for higher moments of inertia. In addition, the second lowest moment of inertia sub-group (0.1 to 0.2 kg·m^2) showed a moderate EO in peak power. As shown by previous works [15, 24, 25], lower moments of inertia led to higher *velocity* and *power*. Thus, it is easier to achieve EO with lower moments of inertia (from 0.01 to 0.2). However, it must be acknowledged that the FRTD shaft type also has an influence on the EO. Nuñez et al. [19] found that although no EO was achieved, the shaft type influenced the *force* and *velocity* exerted with the same moments of inertia. In agreement, our results showed that when an HC device is used, EO is achieved only in peak velocity, but these results were extracted from a single study [50]. In contrast, a higher moderate CON character was observed when the VC was used regarding mean force. This can be explained by the variation in the VC shaft type, from a wider to a narrower radius in CON, and the opposite in ECC, allowing the individual pull with less effort at the beginning of CON.

In summary, EO was not proven to be achieved in most of the papers studied. Indeed, of the works which measured it, not all demonstrated that it had been achieved. Our results showed that EO measurement is dependent on the monitored mechanical variable. What is more, it is influenced by the FRTD shaft-type and moment of inertia used.

Limitations and future directions

Some potential limitations of this meta-analysis should be acknowledged. Firstly, additional analyses regarding shaft type or inertia were not always possible as less than three studies were available for at least one moderator. Secondly, even though the included studies did not specify any negative responses associated with the intervention, it is unclear if there was an attempt by the researchers to record all possible adverse events comprehensively. Therefore, future studies are encouraged to be fully transparent regarding any injuries, pain, or other adverse effects occurring as a result of flywheel use. Thirdly, although most of the included studies in our meta-analysis were classified as having low-moderate risk of bias and moderate-good methodological quality, none of the studies were classified as having excellent methodological quality. Future studies on this topic should strive for greater methodological quality in their designs.

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CONCLUSIONS

For many years, FRTD have been used with the objective of producing EO. However, we found that EO is only shown by peak variables, more specifically in *power* or *velocity*. Indeed, it is more suitable to use lower moments of inertia (i.e., from 0.01 to 0.2 kg·m^2) and an HC device to achieve EO. In contrast, a VC can help in achieving more significant CON outputs. These results are relevant for real practice to decide the best option regarding the FRTD type and load to be used, especially when the main purpose is to achieve EO during RT programmes. Furthermore, the calculation of the E:C-r can provide interesting insights to quantify the EO, even in real time. In addition, although no EO is achieved during the movement, this ratio can express the eccentric character of the execution, which is also important for physical conditioning.

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