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Resistance Training as a Countermeasure in Women with Gestational Diabetes Mellitus: A Review of Current Literature and Future Directions

Brittany R. Allman[1,2,3], **Samantha McDonald**[4], **Linda May**[5,6,7], **Elisabet Børsheim**[1,2,3,8]

[1]Arkansas Children's Nutrition Center, Little Rock, AR, USA

[2]Arkansas Children's Research Institute, Little Rock, AR, USA

[3]Department of Pediatrics, University of Arkansas for Medical Sciences, Little Rock, AR, USA

[4]School of Kinesiology and Recreation, Illinois State University, Normal, IL, USA

[5]Department of Obstetrics and Gynecology, East Carolina University (ECU), Greenville, NC, USA

[6]Department of Kinesiology, ECU, Greenville, NC, USA

[7]Department of Foundational Sciences and Research, ECU, Greenville, NC, USA

[8]Departments of Geriatrics, University of Arkansas for Medical Sciences, Little Rock, AR, USA

Abstract

Gestational diabetes mellitus (GDM) poses a significant health concern for both mother and offspring. Exercise has emerged as a cornerstone of glycemic management in GDM. However, most research regarding this topic examines aerobic training (AT), despite substantial evidence for the effectiveness of resistance training (RT) in improving dysregulated glucose in other groups of people with diabetes, such as in type 2 diabetes mellitus (T2DM). Thus, the purpose of this paper is to review research that examined the impact of RT on markers of glucose management in GDM, and to discuss future research directions to determine the benefits of RT in GDM. Based on the current evidence, RT is effective in reducing insulin requirement, especially in overweight women, reducing fasting glucose concentrations, and improving short-term postprandial glycemic control. However, the number of studies and findings limit conclusions about the impact of RT on risk of GDM, fasting insulin concentrations, insulin resistance, β-cell function, and intra-exercise glucose management. Overall, current evidence is accumulating to suggest that RT is a promising non-pharmacological tool to regulate circulating glucose concentrations in women with GDM, and a potential alternative or supplement to AT.

✉Brittany R. Allman, ballman@uams.edu.

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Conflicts of interest/competing interests Brittany R. Allman has created a podcast about exercise and health-related outcomes ('BENT by Knowledge') and is also the Senior Innovation Scientist for Breakout Lifestyle Fitness, Little Rock, a gym emphasizing RT and health-related outcomes. Samantha McDonald, Linda May, and Elisabet Børsheim report no conflicts of interest or competing interests.

1 Introduction

Gestational diabetes mellitus (GDM) is defined as glucose intolerance that is first diagnosed during pregnancy [1]. GDM is the most common metabolic disorder during gestation, complicating nearly 10% of all pregnancies [2], and the prevalence of GDM is on the rise in the US [3, 4]. Once diagnosed with GDM, the risk of GDM in subsequent pregnancies increases by 35–50% [5, 6] and the risk of developing postpartum type 2 diabetes mellitus (T2DM) increases by 40–60% [7, 8]. Furthermore, the development of GDM poses significant health risks not only to the mother but also the offspring [9, 10]—a finding supported by the Developmental Origins of Health and Disease (DOHaD) and Maternal Resources Hypotheses [11], where fetal exposure to an altered intrauterine environment (e.g., during GDM) impacts offspring health and long-term disease susceptibility (e.g., hypertension, dyslipidemia) [12–17]. Consequently, there is a pressing need for cost-effective therapeutic interventions for GDM. Exercise is known to be effective for the management of glucose in populations with dysregulated glucose levels, such as T2DM. Although aerobic training (AT) is the most common modality used in exercise studies, other forms of exercise, such as resistance training (RT), have emerged as promising tools with which similar outcomes can be achieved. Like T2DM, GDM is characterized by insulin resistance [18, 19]; therefore, RT may be just as beneficial as AT, although research in this area is new. In addition, no review to date has focused exclusively on the impact of RT in GDM, and available reviews lack analysis and discussion of the effect of RT on important markers of glucose regulation in GDM. Thus, the purpose of this paper was to review the impact of RT on markers of glucose management in GDM and discuss the directions for future research to determine the benefits of RT in this population.

2 Current Treatment Strategies for Glucose Management in Women with Gestational Diabetes Mellitus (GDM)

Current treatment for GDM per the American College of Obstetricians and Gynecologists (ACOG) includes diet therapy, self-monitoring of postprandial capillary blood glucose concentration, and exercise recommendations emphasizing aerobic (30 min of moderate-intensity aerobic exercise at least 5 days/week, or a minimum of 150 min per week; walk 10–15 min after each meal) [20]. Others also include RT in their recommendations (at least 2 days per week, 5–10 exercises at 8–15 repetitions at moderate intensity) [21]. If these measures are ineffective at controlling blood glucose levels, then pharmacological therapy (insulin, metformin) is prescribed [20]. Although effective in managing glucose concentrations, pharmacological therapy is associated with increased incidence of adverse outcomes, such as small-for-gestational-age offspring [22]. Moreover, glucose-lowering drugs typically manage hyperglycemia without addressing the underlying metabolic disturbance, which is the combination of a progressive reduction in peripheral and liver insulin sensitivity and impaired insulin action at the post receptor level [22]. Since muscle tissue is one of the primary sites for the reduction in insulin sensitivity throughout pregnancy [23], and exercise improves peripheral glucose tolerance through both insulin-dependent and insulin-independent mechanisms [24], several exercise and pregnancy organizations (e.g., ACOG [25] and the American College of Sports Medicine [ACSM] [26]) endorse the use of prenatal exercise as a non-pharmacological adjunctive therapy for regulating glucose. Specifically, both ACOG and ACSM recommend that pregnant women with uncomplicated pregnancies engage in not only AT but also RT [25, 26], with one of the benefits being a reduction in the risk of GDM. The initial treatment guidelines for GDM diagnosis also consist of recommendations for both AT and RT [20, 21]; however data on RT in this population are still sparse [21], even though research has demonstrated potent benefits of RT on glucose regulation in populations with similar complications in glucose management, such as T2DM.

3 Support for the Effectiveness of Resistance Training (RT) in Individuals with Type 2 Diabetes Mellitus

To support the use of RT in the management of glycemia in GDM, a discussion of the effectiveness of RT in other diabetic populations is helpful. In individuals with T2DM, the improvement in glucose regulation and insulin sensitivity as a result of RT can occur independently of both (1) the incorporation of AT into an exercise regimen [27], and (2) any change in maximal oxygen uptake [28]. Furthermore, the impact of RT on insulin sensitivity and glucose control may be greater in RT compared with AT [29, 30], or, at a minimum, may elicit the same effects on glycemic control [31] when matched for training units or time. Thus, RT seems to be equally effective at managing glucose levels as the commonly prescribed AT. In addition, many of the benefits of RT on measures of glucose control have been found to occur independently of significant increases in muscle mass [32] and after only one RT session or a single set of exercises [33]. Therefore, RT is a promising lifestyle strategy to improve glycemia in T2DM (reviewed extensively by others [34, 35]) even in an acute setting, and may be just as beneficial as AT for combatting insulin resistance [18, 19].

4 Use of Exercise to Manage Glucose in Women with GDM

AT has historically been the preferred exercise modality recommended by most pregnancy, exercise, and diabetes professional advisory bodies to attenuate GDM-related issues [21, 36–38]; however, other forms of exercise such as RT have also shown promise for glucose control in women with GDM. For instance, in several studies, RT has been shown to elicit similar improvements in glycemic control compared with AT [39–42], indicating that RT alone may be an approach to achieving the same glycemic outcome using a different stimulus. Furthermore, a recent meta-analysis determined that as long as the training (either AT or RT) is performed for the proper frequency (three to four times per week), intensity (moderate to vigorous), and time per session (20–30 min), similar glycemic outcomes in women with GDM will occur [41]. Therefore, if the dosage of exercise (frequency, intensity, time, and volume) is appropriate, the type of exercise is not as important with respect to glucose regulation. These findings are critical and exciting for this growing field because they allow for the personalization of exercise programs based on preference, without boxing women into a one-size-fits-all approach to prenatal exercise. For example, women may choose to participate in RT only in late gestation if they are unable to tolerate the joint and pelvic floor impact and metabolic cost of steady-state AT, but still glean similar glycemic benefits. The remainder of this review will be focused on reviewing studies that have explored this relationship and then reviewing considerations for future research.

5 Studies Examining the Use of RT to Regulate Glucose in GDM

This review was conducted using the PubMed and Google Scholar search engines in the month of June 2021 for manuscripts with no date range. The keywords used to search were ‘resistance training’, ‘GDM’, ‘gestation diabetes mellitus’, ‘maternal’, ‘insulin’, and ‘glucose’. We considered all intervention and observational studies assessing the effects of prenatal RT on maternal glycemia, whether RT was used as the sole training modality or used in concert with AT. RT was defined as exercise that causes the muscles to exert force against an external resistance, while AT was defined as exercises that cause large muscle groups to move in a rhythmic manner for a sustained period of time. All classifications of maternal BMI were accepted. Studies that provided dietary interventions in combination with exercise interventions were also considered. Primary outcome measures included risk of GDM, insulin requirement, fasting circulating insulin and glucose concentrations, insulin resistance, insulin sensitivity, β-cell function, and postprandial, post-exercise, and intra-exercise glycemia.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram of studies selected for analysis is shown in Fig. 1. There were 1012 records identified using search engines (PubMed and Google Scholar) and five records were identified using other sources (e.g., references in reviews, meta-analyses). Five records were eliminated because of duplication, therefore 1012 records were screened. Overall, 911 records were excluded for not being full-text original articles specific to RT and pregnancy-related outcomes, leaving 101 eligible full-text articles. A further 90 were excluded because they were out of scope (e.g., physical activity, not glucose-related), leaving 11 articles for evaluation. These studies and their primary outcome measures are reviewed below, and the descriptions of these randomized controlled trials are outlined in Table 1.

Other reviews have focused on all forms of exercise (e.g., AT and RT) [41, 43–46] but do not focus on the effectiveness of RT alone. Furthermore, a specific review by Yaping et al. [47] focused exclusively on the effects of RT in pregnant women but not GDM specifically, and further only discussed 3 of the 10 manuscripts reviewed in the current study. In addition, Yaping et al. [47] focused on fasting blood sugar, average 2-h post-meal blood glucose, insulin dosage, and rate of insulin injection as the main outcome variables. The current review includes each of these outcomes, in addition to risk of GDM, fasting insulin concentrations, insulin resistance, β-cell function, and intra-exercise glycemic control. Therefore, the current review is novel by providing an up-to-date review of studies that have assessed the impact of RT, exclusively, on numerous metabolic outcomes specific to glucose regulation in GDM.

5.1 Long-Term Effects

5.1.1 Risk of GDM1—Three studies assessed the effect of RT on the risk of GDM (Table 1) [48–50], with two studies identifying a reduction in the risk of GDM in the RT/AT groups compared with the control groups [48, 50], and one describing no difference in the risk of GDM between groups [49]. Garnæs et al. [50] exercised obese women with GDM using a moderate-intensity RT/AT program, and noted a significant reduction in the incidence of GDM in the RT/AT group compared with the control group {RT/AT: 2 cases, 6.1%; controls: 9 cases, 27.3%, with an odds ratio (OR) of 0.1 (95% confidence interval [CI] 0.02–0.95; $p = 0.04$)}. These findings were confirmed by Barakat and colleagues [48] in healthy-weight women, but significance was lost after adjustment for maternal age and pre-pregnancy bodyweight (OR 0.84, 95% CI 0.50–1.40, $p = 0.496$) [48]. Although the participants in this study were compliant with the exercise protocol (> 95%), the RT protocol performed three times per week for 25–30 min per session was termed ‘toning and joint mobilization’ and included the following exercises: shoulder shrugs and rotations, arm elevations, leg lateral elevations, and pelvic tilts and rocks. These exercises are isolation movements targeting very small muscle groups and were performed at what was described as moderate intensity (Borg Scale Rating of Perceived Exertion [RPE]: 10–12). However, exercises were performed with very small barbells (3 kg) and low-to-medium resistance bands (1–3 kg of resistance). Therefore, although it may be speculated that the individual RT sessions acutely improved glucose uptake, the ability of the RT program to create a physiological stimulus large enough to evoke chronic adaptations (e.g., increased lean mass) that would result in a reduced risk of GDM in otherwise healthy, lean women may have been unlikely. Even so, another group (Stafne et al. [49]) confirmed that an RT/AT intervention was insufficient in reducing the prevalence of GDM in both healthy weight and overweight women (RT/AT: 25 of 375 [7%, 95% CI 4.3–9.7]; controls: 18 of 327 [6%, 95% CI 3.3– 8.6]), even after conducting a subgroup analysis of women who were adherent to the exercise program. However, this study did not examine the potential differences in GDM prevalence between healthy weight and overweight women, and the women exercised less than the recommended level (e.g., < 150 min/week). In summary, it is difficult to make conclusions about the effectiveness of RT on the risk of GDM because the three studies reviewed combined RT with AT and provided varying results. However, there may be an effect of RT on the risk of GDM in women with obesity.

5.1.2 Insulin Requirement—The three studies that assessed how RT during pregnancy in women with GDM impacted the use of insulin therapy throughout the intervention showed conflicting results (Table 1) [51–53]. Whereas de Barros et al. [51] and Huifen et al. [53] demonstrated a decrease in the number of women who required insulin in the RT group compared with the control group, Brankston et al. [52] found no differences in the number of women who required insulin between an RT-plus-diet group vs. diet alone). The diet intervention in the Brankston et al. [52] study consisted of a standard diabetic diet, with 40% of total energy intake (TEI) from carbohydrates, 20% of TEI from protein, and 40% of TEI from fat (24–30 kcal/kg/day), spread over three meals and three snacks. The details of the Brankston et al. [52] and de Barros et al. [51] studies were nearly the same: participants in both studies were overweight, started circuit RT using elastic bands around the same time (de Barros et al. [51]: 31 weeks of gestation; Brankston et al. [52]: 29 weeks of gestation), continued until birth, at a frequency of three times per week, with a similar progression (two circuits in the first 2 weeks, three circuits thereafter until birth) and rest between exercises (up to 1 min). However, intensity (de Barros et al. [51]: moderate to vigorous; Brankston et al. [52]: moderate) and compliance (de Barros et al. [51]: 80%; Brankston et al. [52]:

67%) were different. Therefore, higher intensity and compliance with a higher-intensity program may be required to reduce insulin requirement in women with GDM. Differences in findings may have also been attributed to extraneous variables such as body mass index (BMI), because in a subgroup analysis of healthy weight and overweight participants, Brankston et al. [52] determined that overweight women had a significantly lower incidence of insulin therapy use in the RT-plus-diet group (3 of 10) compared with the diet-only group (8 of 10). Therefore, it seems that women with obesity-related GDM have greater improvements in peripheral insulin sensitivity when RT is incorporated as an intervention, and thus RT plus diet may have additive or synergistic effects. These findings are not surprising, considering the mechanical nature of skeletal muscle contractions facilitates the improvement in insulin sensitivity, and thus reduces the requirement for insulin [54]. Aside from the number of women requiring insulin, Brankston et al. [52] also demonstrated that the women in the RT-plus-diet group were prescribed less insulin and commenced insulin therapy later after diagnosis, compared with the diet-only group. Likewise, Huifen et al. [53] determined that the use of insulin (units per day) was lower in RT compared with the control groups. Therefore, it seems that RT in women with GDM may impact the necessity of pharmacological insulin, the amount required, and when it is commenced.

5.1.3 Fasting Circulating Glucose and Insulin Concentrations—Current available studies suggest that RT during pregnancy in women with GDM is associated with lower fasting glucose concentration (Table 1). While de Barros et al. [51] found a non-significant tendency to lower glucose levels throughout the day in an RT group versus a control group, three other studies found that RT significantly lowers circulating glucose concentration [53, 55, 56]. Huifen et al. [53] determined that mean fasting glucose after an intervention was lower in RT (RT 3 × /week for at least 6 weeks) compared with the control group. Refaye et al. [55] found that not only was there a decrease in fasting circulating glucose levels in RT but a decrease was also observed in AT. However, they found a significantly greater decrease in fasting glucose levels in the RT group (22%) compared with the AT group (5%) when matched for exercise time [55]. In two papers on the same cohort, Kazemi and Ali Hosseini [56] and Kasraeian et al. [57] reported no significant difference in fasting glucose concentrations between aqua RT, aqua AT, and control groups. The aqua AT group consisted of slow walking and moderate-intensity aerobic exercises in water, while the aqua RT group consisted of circuit training using an elastic band focusing on the main muscle groups in a circuit of eight exercises performed 15 times with 30–60 s of rest between circuits. After comparing the longitudinal change in glucose concentrations in groups individually, glucose concentrations significantly decreased after 6 weeks of aqua RT but not with aqua AT [56, 57]. Although it is difficult to compare the volume of exercise between RT and AT, it is important to note that the volume of work completed in the aqua RT group was likely greater than the volume of work completed in the aqua AT group from these studies and this should be considered. Overall, studies support that RT in women with GDM may improve fasting glucose concentrations.

Reports of an effect of RT on fasting insulin concentrations are more variable. For instance, Kazemi and Ali Hosseini [56] found no differences in fasting insulin concentrations between the aqua RT, aqua AT, and control groups, while Kasraeinan et al. [57] demonstrated a significant difference between groups (RT, AT, controls) in the same cohort. Discrepancies in results between these two reports of the same study (Kazemi and Ali Hosseini [56] and Kasraeinan et al. [57]) are unclear but are likely due to the statistical approach used (Kazemi and Ali Hosseini [56] using Kruskal–Wallis: 0.031; Kasraeinan et al. [57] using ANCOVA: 0.31). Regardless of differences in the reported significance level, within-group changes in insulin concentrations were the same, with a non-significant increase in insulin levels throughout the RT intervention and a non-significant reduction in insulin levels throughout the AT intervention. On the other hand, Stafne et al. [49] showed significantly lower fasting insulin levels with a combination of RT (20–25 min) and AT (performed for 30–35 min with low impact) compared with a standard antenatal care control group; however, the differences were halved after adjusting for baseline levels. Each of the mentioned studies included healthy weight/overweight women who exercised at a moderate intensity three times per week until late gestation (compliance and progression could not be compared because of missing data). Stafne et al. [49] differed from Kazemi and Ali Hosseini [56]/Kasraeinan et al. [57] in that participants performed RT for less time (Stafne et al. [49]: 20–25 min per session; Kazemi and Ali Hosseini [56]/Kasraeinan et al. [57]: 30–45 min per session), although total session length was longer in the study by Stafne et al. [49] with the additional AT (total RT + AT ~ 50–60 min per session) and the use of different modalities (Stafne et al. [49]: bodyweight; Kazemi and Ali Hosseini [56]/Kasraeinan et al. [57]: elastic bands). As mentioned above, comparison of exercise volume (repetitions × sets × resistance) between studies may enhance overall comparisons of outcomes; however, these studies used either bodyweight or elastic bands, which do not allow for the precise calculation of volume because weight and/or resistance are largely unknown. Furthermore, participants in the Stafne et al. [49] study were not compliant with the exercise program (55% compliance), which consisted of a mix of in-person and at-home workouts. Therefore, compliance with the training program could have impacted the responsiveness of women with regard to exercise-induced improvements in circulating insulin concentrations. Thus, although it is difficult to deduce why differences were noted in insulin concentrations between the Kazemi and Ali Hosseini [56]/Kasraeinan et al. [57] and Stafne et al. [49] studies, it may be that the cumulative effect of RT plus AT is more beneficial than RT alone with respect to circulating insulin concentrations, and compliance and volume of the exercise program should be taken into account. Due to the discrepancies in findings, conclusions on the effectiveness of RT in GDM on fasting insulin concentrations cannot be made.

5.1.4 Insulin Resistance and β-Cell Function—The Kazemi and Ali Hosseini [56]/Kasraeinan et al. [57] and Stafne [49] studies also used the homeostatic model assessment (HOMA) of insulin resistance (HOMA-IR) to estimate insulin resistance (Table 1); however each publication reported different effects of RT on insulin sensitivity that exactly match the respective findings with insulin concentrations (see Sect. 5.1.3). For example, Kazemi and Ali Hosseini [56] noted that HOMA-IR was not different between groups (aqua RT, aqua AT, controls), while Kasraeinan et al. [57], using the same cohort, showed that there was a significant difference in HOMA-IR between groups, and Stafne et al. [49] showed that HOMA-IR was lower in the RT plus AT group but differences disappeared after adjusting for baseline HOMA-IR. Importantly, the argument of discrepancy of findings between Kazemi and Ali Hosseini [56] and Kasraeinan et al. [57] are the same as noted in Sect. 5.1.3

(i.e., reported values are the same but statistical methods to compare groups slightly differ), and it is likely that the same variables need to be taken into account when considering the impact of an exercise program on markers of insulin resistance (e.g., compliance, length of time spent on RT, combination of RT and AT). Similarly, discrepancies in results preclude definitive conclusions about the effectiveness of RT in GDM on HOMA-IR.

HOMA-β, an estimate of steady-state β-cell function, was not significantly different between the aqua RT, aqua AT, and control groups in the publications by Kazemi and Ali Hosseini [56] and Kasraeinan et al. [57] but increased significantly throughout the program within the aqua RT group, although not in the other groups (aqua AT, controls). These discrepancies occurred even though aqua RT and aqua AT were performed at the same intensity (50–70% maximal heart rate [HR_{max}]). In summary, conclusions cannot be made about the impact of RT in GDM on HOMA-β.

5.2 Short-Term Effects: Postprandial and Intra-Exercise Glycemic Control

Several studies have shown that glycemic control is improved with RT during pregnancy in women with GDM (Table 1). de Barros et al. [51] measured capillary blood glucose in pregnant women four times per day—after an overnight fast, 2 h after breakfast, 2 h after lunch, and 2 h after dinner. Investigators then quantified how often participants maintained fasting glucose levels of ≤ 95 mg/dL and postprandial glucose levels of ≤ 120 mg/dL throughout the study, based on American Diabetes Association (ADA) guidelines [58]. These researchers found that women who participated in RT demonstrated better glycemic control, reflected in a greater percentage of weeks spent within the target glucose range when compared with the control group (RT: 63 ± 30%; control: 41 ± 31%) [51]. Furthermore, women in the RT group who used insulin therapy also had more weeks of adequate glycemic control compared with women in the control group using insulin therapy [51]. Likewise, Huifen et al. [53] found that mean 2-h postprandial glucose (average blood glucose 2 h after three meals) was lower in RT compared with the control group. In addition, Sklempe Kokic and colleagues [59] found that although there was no difference in the levels of fasting glucose between experimental groups (RT + AT vs. controls), postprandial glucose levels at the end of pregnancy were lower in the exercise group compared with the control group. Furthermore, Refaye and co-workers [55] reported a decrease in 2-h postprandial circulating glucose levels after both RT and AT interventions. However, these researchers found that there was a significantly greater decrease in 2-h (33%) glucose levels in the RT group compared with the AT group (4%) [55]. Therefore, study findings suggest that RT in GDM likely improves postprandial glycemic control.

Regarding intra-exercise glycemic control, it seems that exercise training during pregnancy does not negatively impact glycemia during exercise sessions. For instance, Sklempe Kokic et al. [60] measured glucose levels before and after an acute RT session and found that glucose levels decreased from baseline; however, there were no differences between the exercise (RT + AT) and non-exercise control groups [60]. In summary, it seems that RT in GDM neither benefits nor negatively impacts the handling of carbohydrate nutrients post-exercise.

6 Considerations for Future Research Regarding the Use of RT in Women with GDM

6.1 Muscular Performance Testing and Modality

The goal of most RT programs is to improve muscular performance (e.g., strength, endurance, power), and RT programs often improve performance in tandem with insulin sensitivity [61]. However, none of the available studies tested muscular performance and therefore there is no way to confirm that the RT program improved these measures. Because a moderate level of muscular strength is associated with a lower risk of T2DM compared with low levels of muscular strength [62], it will be important that future research in women with GDM examines the extent to which the prescribed RT programs actually improve muscular strength. In addition, the modality of RT should be considered. For example, in the available studies, most RT programs used elastic bands that applied anywhere from 0.5 to 5 kg of external resistance, dumbbells no greater than 3 kg, or bodyweight with virtually no increases in external resistance throughout the program. Under such conditions, with no strategic progression, marginal improvements in muscular strength are expected and would plateau in a population that has minimal strength and is new to exercise, such as sedentary pregnant women and the elderly [63]. Furthermore, the studies reviewed in this report and studies in other populations (e.g., aging) employ the use of therapeutic elastic bands with minimal resistance, unlike the heavy resistance elastic bands used to supplement traditional RT in populations such as fit individuals. Since the strength- and hypertrophy-related progression potential of elastic bands varies [64], it may be more optimal for improvements in muscular performance to (1) start a program with resistance bands and progress to other forms of RT, such as free weights or machines; (2) more strategically progress resistance band-based programs; or 3) use resistance bands as a supplement to traditional RT programs.

6.2 Supervision of the Program

Direct, in-person supervision of exercise sessions, or at a minimum, regular contact and accountability throughout the RT intervention, seems to be critical to maintain compliance with the exercise protocol and thus the potential RT effect on glycemic regulation in the prevention and/or management of GDM. One study involving individuals with T2DM noted reduced adherence to the frequency (number of weekly sessions) and intensity of the exercise sessions with home-based RT programs (which had limited supervision) that ultimately led to a lower magnitude of effect on glycemic control [65]. In another study in women with GDM, findings were similar [49], underscoring the importance of adherence to RT protocols in order to test efficacy in terms of improving glycemic control during pregnancy. In support of these findings, women with GDM who participated in supervised exercise sessions at least three times per week for at least 40 min/session had more optimal glycemic outcomes compared with participants who were not supervised [52]. Therefore, there is convincing evidence that supervision of exercise sessions is critical to achieve acceptable adherence to an exercise program, and yet it is uncommon to have qualified exercise physiologists or prenatal exercise specialists available on site at antenatal centers. Thus, exercise recommendations fall in the hands of the obstetric provider. However, these professionals may not be aware of the current research literature or the recommended exercise guidelines for pregnancy or have time to share [66, 67]. Accordingly, it will be important for future community research to focus on how prenatal exercise specialists can be involved in the dayto-day prenatal exercise program in a fitness facility or home setting. Additionally, exercise adherence could be improved by developing programs that are assisted by medical health insurance providers, such as Silver Sneakers®. Development of more randomized controlled trials and multicenter studies that describe the benefit of RT on improvement of maternal outcomes, labor and delivery, and other outcomes may eventually lead to the development of prenatal exercise programs covered by health insurance that focus on supervised one-on-one training. In that way, several barriers to consistent exercise participation (e.g., fitness, professional supervision, financial, personal support) could be removed and exercise adherence could be improved in a setting that is conducive to direct supervision by certified prenatal exercise professionals.

6.3 Exercise Intensity

Currently, the general consensus is that moderate-intensity exercise is safe for pregnant women who are otherwise healthy and have a healthy pregnancy [68]. Furthermore, ACOG reports that exercise does not increase the risk of miscarriage, low birth weight, or early delivery, which were common concerns in the past [68]. However, exercise should always be discussed with the obstetric provider during prenatal visits and women should receive medical clearance prior to initiating or continuing exercise when pregnant [68].

To date, light- and moderate-intensity RT are deemed safe during pregnancy; however, research has not examined the safety of higher intensities of RT for pregnant women. Of the RT studies that were discussed in Sect. 5, none reported adverse events caused by the RT program. These findings may help shape current perceptions around RT during pregnancy. Indeed, there may be a negative stigma associated with pregnant women participating in intense RT, such as CrossFit. For example, pregnant women who participate in this type of training note that overcoming judgments and stereotypes was a large part of their experience [69]. While it is likely that women participating in vigorous RT such as CrossFit were already vigorously active prior to pregnancy, little is known about implementing higher-intensity RT programs in GDM. Therefore, future research should examine higher-intensity RT programs in GDM populations.

6.4 Longitudinal Follow-Up of Children Born to Mothers Who Performed Gestational RT

The DOHaD theory states that environmental insults in early life may contribute to the long-term risk of disease in the offspring [70]. Lifestyle factors such as exercise, or lack thereof, during pregnancy can significantly affect the programming of metabolism and disease risk in the offspring in the short- and long-term. Several studies have examined the impact of prenatal exercise in maternal obesity on offspring metabolism [71–92]; however only six of these reports were in humans [71–76], while the remaining 16 of 22 studies used rodent models [77–92]. Importantly, each of these studies assessed the impact of AT, while none assessed the impact of RT. Furthermore, there are no studies that examined this relationship in women with GDM. Thus, data regarding the effect of RT on metabolic programming of offspring born to women with GDM are lacking.

7 Conclusions

Based on the current evidence, findings suggest that RT in women with GDM has therapeutic potential to reduce insulin requirement especially in overweight women, reduce fasting glucose concentrations, and improve short-term postprandial glycemic control. Based on the limitations of the current studies, definitive conclusions about the impact of RT on the risk of GDM, fasting insulin concentrations, insulin resistance, β-cell function, and intra-exercise glucose management cannot be made. Furthermore, future research should address these gaps, including the degree of increased muscular strength, the impact of supervision on session and intensity compliance, and the impact of RT intensity on glucose regulation. Overall, current evidence is accumulating to suggest that RT may be a promising non-pharmacological tool to regulate circulating glucose concentrations in women with GDM, and a potential alternative or supplement to AT. Furthermore, the data from future studies addressing these gaps will be important for informing professional advisory bodies on exercise guidelines during pregnancy, especially those complicated by GDM.

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Key Points

Resistance training (RT) may be an effective tool in women with gestational diabetes mellitus (GDM) to reduce insulin requirement, reduce fasting glucose concentrations, and improve short-term postprandial glycemic control; however, the impact of RT on other outcomes (e.g., risk of GDM, fasting insulin concentrations, insulin resistance, β-cell function, and intra-exercise glucose management) is still unknown

To determine the true efficacy of RT in GDM, future research should determine the degree to which RT increases muscular strength, the impact of supervision by a fitness professional on session and intensity compliance, and the impact of RT intensity on glycemic outcomes of interest, such as risk of GDM, fasting insulin concentrations, insulin resistance, β-cell function, and intra-exercise glucose management

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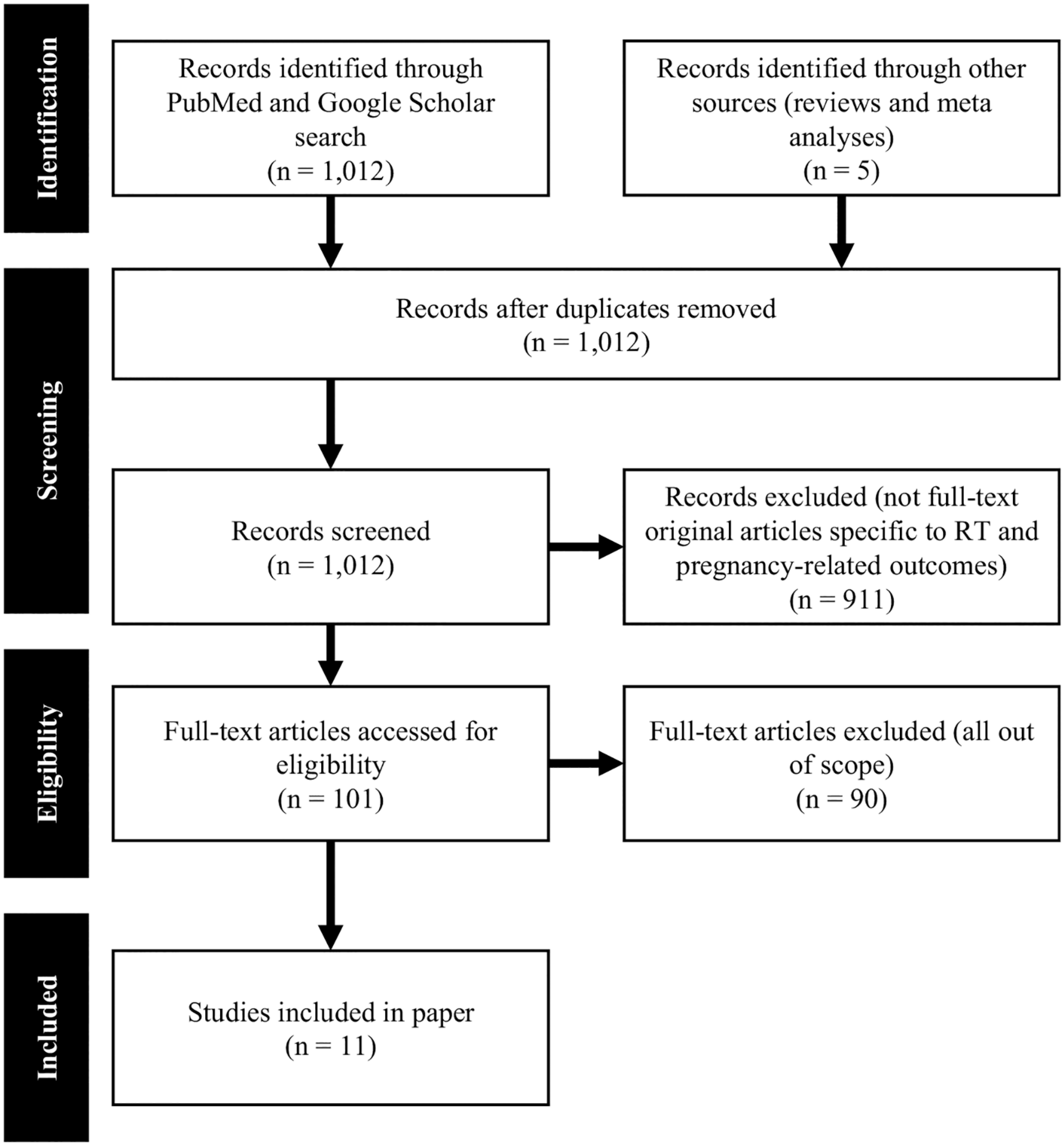

Fig. 1.

PRISMA flow diagram of studies selected for analysis. *PRISMA* Preferred Reporting Items for Systematic Reviews and Meta-Analyses, *RT* resistance training

Table 1

Description of randomized controlled trials assessing the impact of resistance training during pregnancy on glycemia in women with gestational diabetes mellitus

Study, year	BMI	Exercise type and duration	FITT and progression	Description of exercise	Outcomes
de Barros et al., 2010 [51] (n = 64)	OW	CRT vs. CON 31 weeks to birth	Thrice Mod–Vig, RPE 5–6 (scale of 1–10) 30–40 min Bands Weeks 1–2: 2 circuits Week 3–birth: 3 circuits	In-person 1 ×/week, at-home 2× /week. Circuit of 8 exercises (chest, back, biceps, triceps, deltoid, quadriceps, thigh, and calf muscles) performed at 15 reps each, with 30–60 s of rest between exercises	Exercise compliance: 80% Fewer participants required INS in CRT (21.9%) vs. CON (56.3%) [$p = 0.005$] Higher percentage of weeks spent within the proposed target GLU range (defined as at least 80% of weekly measurements below the limits pre-established for the disease) in CRT (63 ± 30%) vs. CON (41 ±31%) [$p = 0.006$] No difference in the amount of INS required (CRT: 0.49 ± 0.14: CON: 0.44 ± 0.11 U/kg; $p = 0.401$), latency to INS requirement (CRT: 2.11 ± 1.64: CON: 1.85 ± 1.21 weeks; $p = 0.715$), or GLU levels (CRT: 102.89 ± 7.88; CON: 100.30 ± 9.37 mg/dL; $p = 0.084$) between groups
Refaye et al., 2016 [55] (n = 50)	OB	CRT vs AT 23–37 weeks	Thrice Mod 30 min Bands Progression NR	In-person *CRT:* Circuit of 8 exercises performed in a seated position (chest pull, shoulder flexion, shoulder abduction, elbow flexion, elbow extension, hip abduction, knee extension, ankle plantar flexion) performed at 10 reps each, with 2 min of rest between circuits *AT:* 40 min of walking on a treadmill at 60% of age-predicted HR_{max}	Exercise compliance: NR Reductions in fasting (pre-intervention: CRT: 91.0 ± 11.2 mg/dL; AT: 91.5 ± 10.9 mg/dL; post-interventions: CRT: 71.4 ± 11.1 mg/dL; AT: 86.5 ± 8.8 mg/dL) GLU levels as a result of the interventions Reductions in 2-h postprandial (pre-intervention: CRT: 172.6 ± 10.5 mg/dL; AT: 169.6 ± 11.9 mg/dL; post-interventions: CRT: 115.4 ± 17.2 mg/dL; AT: 162.2 ± 16.1 mg/dL) GLU levels as a result of the interventions Greater decrease in CRT (fasting GLU percentage changes; CRT: 21.53%, $p = 0.0001$; AT: 5.46%, $p = 0.01$; 2-h postprandial percentage changes; CRT: 33.14%, $p = 0.0001$; AT: 4.39%, $p = 0.01$)
Barakat et al., 2013 [48] (n = 510)	NW	RT/AT vs. CON 10–12 to 38–39 weeks	Thrice Mod, RPE 10–12 (scale of 6–20) 25–35 min Bands, barbells Progression NR	In-person. Circuit of 5 toning and joint mobilization exercises (pelvic tilts, biceps curls, arm extensions, arm side lifts, shoulder elevations, bench press, seated lateral row, lateral leg elevations, leg circles, knee extensions, hamstring curls, ankle flexion and extensions) performed for 1 set of 10–12 reps each	Exercise compliance: > 95% Significantly lower risk of developing GDM in RT/AT (OR 0.62, 95% CI 0.40–0.98, $p = 0.041$) This relationship was lost when adding maternal age and pre-pregnancy bodyweight in the model (OR 0.84, 95% CI 0.50–1.40, $p = 0.496$)
Sklempe Kokic et al., 2018 [59] (n = 36)	NW OW	RT/AT/diet vs. diet 22–36 weeks	Twice Low–Mod, RPE 13–14 (scale of 6–20) 20–25 min Bands, dumbbells, bodyweight Progression NR	In-person and extra walking at home *AT:* 20 min of self-adjusted speed and incline *RT:* 3 × 10–15 reps each. Three resistance exercise protocols interchanged between exercise sessions, including exercises for the trunk, and upper and lower extremity muscles	Exercise compliance: 84% No difference in fasting GLU at the end of pregnancy between groups (RT/AT/diet: 4.32 ± 0.26 mrnol/L; diet: 4.44 ± 0.46 mmol/L: $p = 0.367$) Lower postprandial GLU (average of three postprandial capillary blood samples: 2 h after breakfast, 2 h after lunch and 2 h after dinner) at the end of pregnancy in RT/AT (4.66 ± 0.46 mmol/L) vs. CON (5.30 ± 0.40 mmol/L) [$p < 0.001$]
Sklempe Kokic et al., 2018 [60] (n = 18)	NW OW	RT/AT/diet vs. Diet 22–36 weeks	Twice Low–Mod, RPE 13–14 (scale of 6–20) 20–25 min Bands, dumbbells, bodyweight Progression NR	In-person and extra walking at home *AT:* 20 min of self-adjusted speed and incline *RT:* 3 × 10–15 reps each. Three resistance exercise protocols interchanged between exercise sessions, including exercises for the trunk, and upper and lower extremity muscles	Exercise compliance: 84% Decrease in post-exercise GLU levels vs. baseline levels in the total sample (both groups combined baseline: 4.7 ± 0.6 mmol/L; both groups combined end of exercise: 3.9 ± 0.4 mmol/L; $p < 0.001$) No difference in post-exercise GLU levels between groups ($p = 0.248$) No difference in acute GLU response to exercise between the second and third trimesters in a subgroup that exercised during both trimesters (second trimester: 3.6 ± 0.6 mmol/L; third trimester: 4.0 ± 0.6 mmol/L; $p = 0.515$)

Study, year	BMI	Exercise type and duration	FITT and progression	Description of exercise	Outcomes
Brankston et al., 2004 [52] ($n = 32$)	OW	CRT/diet vs. diet 29 weeks to as long as possible	Thrice Mod NR Bands Week 1: 2 ×15 reps Week 2: 2 × 15 reps Week 3: 3 ×15 reps Week 4–birth: 3 × 20 reps	In-person. Circuit of 8 exercises (plie squats, military press, knee extension, hamstring curl, bench press, lateral pull down, seated row, triceps press) performed at 15–20 reps each, with ~ 1 min of rest between stations	Exercise compliance: 67% No difference in the number of women whose condition required INS therapy between groups (CRT/Diet: 7 [43.8%]: diet alone: 9 [56.3%]; $p = 0.48$) Lower incidence of INS use in OW women with CRT/diet vs. diet alone (CRT/diet: 3 of 10 women; diet alone: 8 of 10 women, $p < 0.05$) Lower amount of INS required (CRT/diet: 0.22 ± 0.2 U/kg; diet alone: 0.48 ±0.3 U/kg; $p < 0.05$) in CRT/diet vs. diet alone Higher latency to INS requirement (CRT/diet: 3.71 ± 3.1 weeks; diet alone: 1.11 ± 0.8 weeks; $p < 0.05$) in CRT/diet vs. diet alone
Kazemi and Ali Hosseini, 2017 [56] ($n = 34$)	NW OW	Aqua CRT vs. Aqua AT vs. CON Duration NR	Thrice Mod, RPE 12–14 (scale of 6–20) 30–45 min Bands Weeks 1–2: 2 circuits Week 3–birth: 3 circuits	In-person *Aqua AT:* 30–5 min at 50–70% HR_{max} *Aqua CRT:* Circuit of 8 exercises of 15 reps each, with 30–60 s of rest between each exercise, 50–70% HR_{max}	Exercise compliance: NR No difference in fasting INS (CRT: pre = 9.8 ± 2.3, post = 10.2 ± 2.7: AT: pre = 8.1 ±2.8, post = 7.8 ±2.5: CON: pre = 12.5 ±3.4, post= 13.8 ± 2.9 mg/dL: $p = 0.31$) between groups No difference in fasting GLU (CRT: pre = 93.8 ± 8.1, post = 87.0 ± 8.1; AT: pre = 83.4 ± 8.4, post = 81.7 ± 6.8: CON: pre = 89.5 ±10.2, post = 89.0 ± 10.5 mg/dL; $p = 0.07$) between groups No difference in HOMA-IR (CRT: pre = 2.2±0.5, post = 2.1 ± 0.5: AT: pre = 1.6 ±0.5, post= 1.5 ± 0.5: CON: pre = 2.7 ± 0.6, post = 3.0 ± 0.6; $p = 0.82$) between groups No difference in HOMA-β (CRT: pre = 129.1 ± 70.4, post = 177.3 ± 99.7: AT: pre = 166.9 ± 77.3, post= 180.6± 170.9: CON: pre = 210.3 ± 129.9, post = 224.1 ± 163.1: $p = 0.43$) between groups Reduction in fasting GLU (CRT: %Δ = −7.1%, $p = 0.01$; AT: %Δ= −1.9%, $p = 0.31$; CON: %Δ = 0%, $p = 0.39$) in CRT, but not AT or CON groups from pre- to post-test Increase in HOMA-β (CRT: %Δ = 38.9%, $p = 0.03$; AT: %Δ = 8.2%, $p = 0.59$; CON: %Δ = 6.5%, $p = 0.06$) in CRT, but not the AT or CON groups from pre- to post-test
Kasraeian et al., 2017 [57] ($n = 34$)	NW OW	Aqua CRT vs. Aqua AT vs CON Duration NR	Thrice Mod, RPE 12–14 (scale of 6–20) 30–45 min Bands Weeks 1–2: 2 circuits Week 3–birth: 3 circuits	In-person *Aqua AT:* 30–5 min at 50–70% HR_{max} *Aqua CRT:* Circuit of 8 exercises of 15 reps each, with 30–60 s of rest between each exercise, 50–70% HR_{max}	Exercise compliance: NR Fasting INS (CRT: pre = 9.81 ± 2.32, post= 10.22 ±2.76: AT: pre = 8.14 ± 2.82, post = 7.81 ± 2.54; CON: pre = 12.54 ± 3.14, post = 13.81 ± 2.90 MIU/mL; $p = 0.031$) was different between groups HOMA-IR (CRT: pre = 2.26 ± 0.51, post = 2.18 ± 0.58; AT: pre = 1.69 ± 0.58, post=1.57 ± 0.54; CON: pre = 2.76 ±0.69, post = 3.01 ± 0.60; $p = 0.008$) was different between groups Fasting GLU (CRT: pre = 93.81 ± 8.19, post = 87.09 ± 8.17; AT: pre = 83.40 ± 8.42, post = 81.75 ± 6.89; CON: pre = 89.54 ± 10.23, post = 89.00 ± 10.50 mg/dL; $p = 0.075$) were not different between groups HOMA-β (CRT: pre = 129.11 ± 70.44, post = 177.33 ± 99.70; AT: pre = 166.92 ± 77.39, post = 180.64 ± 170.90; CON: pre = 210.39± 129.98, post = 224.17 ± 163.10; $p = 0.438$) were not different between groups Fasting GLU was reduced (same values as above, *p*-values: CRT: 0.012; AT: 0.311; CON: 0.399) in CRT but not the AT or CON groups HOMA-β increased (same values as above, *p*-values: CRT: 0.032; AT: 0.594; CON: 0.068) in CRT but not the AT or CON groups
Stafne et al., 2012 [49] ($n = 702$)	NW OW	RT/AT vs. CON 18–22 to 32–36 weeks	Thrice Mod 20–25 min Bodyweight Progression NR	In-person 1 × /week, and at-home 2 × / week *RT:* 3 × 10 reps of exercises targeting upper and lower limbs, back extensors, deep abdominal muscles, and pelvic floor muscles *AT:* 30–35 min of low-impact Also a 45-min home exercise program at	Exercise compliance: 5% No difference between groups in prevalence of GDM (RT/AT: 25 of 375 [7%]: CON: 18 of 327 [6%]: $p = 0.52$) Lower fasting INS (RT/AT: 13.4 ± 0.3; CON: 14.9 ± 0.4 IU/mL; $p = 0.004$) and HOMA-IR (RT/AT: 2.56 ± 0.06: CON: 2.87 ± 0.09: $p = 0.006$) in RT/AT vs. CON Significance with fasting INS was lost/reduced when adjusting for baseline values (INS: RT/AT: 13.6 ± 0.3: CON: 14.6 ± 0.3 IU/ mL; $p = 0.03$: HOMA-IR: RT/AT: 2.63 ± 0.06: CON: 2.78 ± 0.06: $p = 0.10$) In a subgroup analysis of women who adhered to the RT/AT protocol vs. CON,

Study, year	BMI	Exercise type and duration	FITT and progression	Description of exercise	Outcomes
				least 2 × /week (30 min of AT and 15 min of RT, and balance exercises)	adherent women had: lower fasting INS (estimated mean differences [95% CI]: − 2.3 [− 3.48 to − 1.02: $p = 0.001$]), and lower HOMA-IR (− 0.43 [− 0.17 to − 0.69; $p = 0.001$]), but these differences were halved when adjusting for baseline values, although INS was still lower in RT/AT (− 0.1.2 [− 2.3 to − 0.1; $p = 0.03$]) there was no difference in the prevalence of GDM between groups
Garnæs et al., 2016 [50] (n = 91)	OB	RT/AT vs. CON 12–18 to 34–37 weeks	Thrice Mod 25 min Bodyweight Progression NR	In-person 2 × /week, and at-home 1 × / week *RT:* 3 × 10 reps of squats, push-ups, diagonal lifts on all fours, oblique abdominal crunches, Kegels, with 1 min of rest between each exercise, and 3 × 30 s of 'plank exercise' *AT:* 35 min of treadmill walking/jogging at ~ 80% HR_{max} Also, a 50-min home exercise at least once weekly (35 min of AT and 15 min of RT) and to do daily pelvic floor muscle exercises	Exercise compliance: NR Lower incidence of GDM in RT/AT vs. CON (RT/AT: 5.9%: CON: 27.3%: $p = 0.11$) No difference in fasting GLU [final mean, 95% CI] (RT/AT: 4.6 [4.4–4.8]: CON: 4.5 [4.3–4.7] mmol/L; $p = 0.56$) levels between groups No difference in 120-min GLU (RT/AT: 6.2 [5.6–6.7]; CON: 5.8 [5.3–6.4] mmol/L; $p = 0.40$) levels between groups No difference in fasting INS (RT/AT: 209.0 [179.9–238.2]; CON: 208.4 [177.1–238.9] pmol/L; $p = 0.97$) levels between groups No difference in HOMA2-IR (RT/AT: 3.6 [3.2–4.1]; CON: 3.7 [3.2–4.2]; $p = 0.90$) levels between groups No difference in HbA1c (RT/AT: 5.4 [5.3–5.5]; CON: 5.4 [5.3–5.5]%; $p = 0.41$) levels between groups
Huifen et al., 2022 [53] (n = 99)	NW OW OB	RT vs CON 24–37 weeks	Thrice Mod, RPE 13–14 50–60 min Modality NR Progression NR	In-person 3 × /week for 6 weeks *RT:* RT of six body regions: elbow flexion exercise, ankle extension exercise, resistance exercise of upper limb, leg lift exercise, upper limb dorsiflexion exercise, and leg abduction exercise	Exercise compliance: NR Mean fasting GLU was lower in RT vs. CON (RT: 4.97 ± 0.21; CON: 5.08 ± 0.17 mmol/L; $p = 0.009$) Mean 2-h postprandial GLU was lower in RT vs. CON (RT: 6.06 ±0.22; CON: 6.25 ±0.22 mmol/L; $p < 0.001$) Insulin utilization rate [n (%)] was lower in RT vs. CON (RT: 1 (2.3%); CON: 8 (17.4%); $p = 0.031$) Use of insulin was lower in RT vs. CON (RT: 0.33 ± 2.14; CON: 2.05 ± 5.04 units/ day, $p = 0.02$)

BMI body mass index, *NW* normal weight, *OW* overweight, *OB* obese, *CON* control group, *RT* resistance training, *AT* aerobic training, *CRT* circuit resistance training, *RPE* rate of perceived exertion, *FITT* frequency, intensity, time, type of exercise, *Mod* moderate, *Vig* vigorous, *NR* not reported, *reps* repetitions, HR_{max} maximal heart rate, *INS* insulin, *GLU* glucose, *HOMA-IR* homeostatic model assessment of insulin resistance, *HOMA-β* homeostatic model assessment of β-cell function, *HbA1c* glycated hemoglobin, *GDM* gestational diabetes mellitus, *OR* odds ratio, *CI* confidence interval