Resistance Training and Type 2 Diabetes

Considerations for implementation at the population level

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Aerobic exercise has consistently been shown to improve glucose control (1–3), enhance insulin sensitivity (2,4,5), and improve cardiovascular risk factors such as visceral adiposity (2), lipid profile (6), arterial stiffness (7), and endothelial function (8). Consistent with this evidence, the American Diabetes Association (ADA) recommends that individuals with type 2 diabetes perform at least 150 min of moderate-intensity aerobic exercise and/or at least 90 min of vigorous aerobic exercise per week (9). Although a lifestyle modification of this nature could have substantial impact on the metabolic and cardiovascular health of this population, it is often difficult for those who have been habitually sedentary to adhere to these guidelines. Indeed, a recent population-based study found that only 28% of individuals with type 2 diabetes achieve these recommendations (10). Unfortunately, it is frequently those who would benefit the most from aerobic exercise that have the greatest difficulty performing it. For individuals with severe obesity, arthritis, physical disabilities, and/or diabetes complications, even walking for 20–30 min may be challenging, uncomfortable, and/or painful to perform. With the continued increase in the prevalence of type 2 diabetes (11), it is evident that alternate forms of physical activity that produce similar metabolic improvements to aerobic exercise may be beneficial in the management of this disease.

Resistance training has recently been recognized as a useful therapeutic tool for the treatment of a number of chronic diseases (12–19) and has been demonstrated to be safe and efficacious for the elderly (20,21) and obese (22) individuals. Similar to aerobic exercise, resistance training has been reported to enhance insulin sensitivity (23–25), daily energy expenditure (26,27), and quality of life (20,28). Furthermore, resistance training has the potential for increasing muscle strength (13,29,30), lean muscle mass (31), and bone mineral density (32,33), which could enhance functional status and glycemic control and assist in the prevention of sarcopenia and osteoporosis. However, unlike aerobic exercise, such as walking, resistance training is dependent on equipment, knowledge of exercise technique, and often requires some initial instruction. Subsequently, if resistance training is going to be a realistic form of exercise for individuals with type 2 diabetes, research is needed to discover practical, sustainable, and economically viable ways to safely implement resistance training at a population level. Therefore, the primary aim of this review was to examine the available literature to investigate whether resistance training is an effective form of exercise for managing glucose homeostasis in individuals with type 2 diabetes. Furthermore, a secondary aim was to also consider strategies and areas for future research to assist with the implementation of resistance training at the population level.

RESISTANCE TRAINING FOR THE MANAGEMENT OF TYPE 2 DIABETES— To examine whether resistance training is an effective form of exercise for managing glucose homeostasis in type 2 diabetes, a comprehensive review of the literature was performed using four electronic databases (MedLine, EMBASE, CINAHL, and Sports Discus). A number of key word combinations were searched within these databases associated with "diabetes mellitus," "type 2 diabetes," "noninsulin dependent diabetes mellitus," "resistance training," "strength training," "physical activity," and "exercise." These searches produced a substantial volume of literature, which was subsequently limited to resistance training studies recruiting individuals with type 2 diabetes written in English. Twenty-four studies were identified, but 4 were excluded (34–37), as they did not report the effects of resistance training on HbA_{1c} (A1C), insulin sensitivity, and/or body composition. The remaining 20 studies (22,38–56) are included in this review and/or summarized in Table 1.

Early studies offered preliminary evidence for the beneficial effects of resistance training (45,46,50,52); however, these studies often had significant methodological limitations. Erikkson et al. (46) demonstrated that 3 months of moderate-intensity circuit resistance training decreased A1C from 8.8 to 8.2%. This reduction in A1C was likely due to improvements in lean body mass, as a strong inverse correlation ($r = -0.73$; $P < 0.05$) was observed between A1C and muscle cross-sectional area posttraining. Similarly, Honkola et al. (50) reported that 5 months of progressive circuit resistance training significantly lowered LDL cholesterol and reduced fasting triglycerides compared with a nonexercising comparison group. Even though no significant reduction in A1C was observed, the difference in A1C between the exercise and comparison groups pre- to postintervention was significant, primarily due to a 0.4% rise in the nonexercising group ($P < 0.01$).

In the first randomized controlled trial (RCT), Dunstan et al. (45) reported

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Abbreviations: ADA, American Diabetes Association; RCT, randomized controlled trial.

A table elsewhere in this issue shows conventional and Système International (SI) units and conversion factors for many substances.

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Table 1—*Summary of resistance training–only or resistance training plus aerobic training studies*

Source	*n*/design	Study length	Exercise prescription	Primary findings	Secondary findings
Resistance training–only trials					
Eriksson et al. (46)	8/NTD	Two times/week for 3 months	CWT, 11 exercises, intensity >50% PME; 1 set of 15–20 repetitions; 30 s rest between exercises	↓ in A1C with RT; (8.8 ± 1.4 to 8.2 ± 1.4%, $P < 0.05$)	↔ in HDL, LDL, fasting blood glucose, triglycerides, or BMI
Honkola et al. (50)	38: 18 RT and 20 control subjects/NRCT	Two times/week for 5 months	CWT, 8–10 exercises, intensity = moderate; 2 sets of 12–15 repetitions; 30 s light cycling between exercises	↔ in A1C with RT (7.5 ± 0.3 to 7.4 ± 0.2%); Δ in A1C with RT was different from control, $P < 0.05$	↓ LDL, triglycerides, and total cholesterol with RT ($P < 0.05$); ↔ in BMI; ↑ in HDL in control
Dunstan et al. (45)	27: 15 RT and 12 control subjects/RCT	Three times/week for 8 weeks	CWT, 10 exercises, intensity 50–55% 1 RM; weeks 1 and 2, 2 sets of 10–15 repetitions; weeks 3–8, 3 sets of 10–15 repetitions; 30 s rest between exercises	↔ in A1C with RT (8.2 ± 0.5 to 8.0 ± 0.5%); ↔ in A1C in control (8.1 ± 0.6 to 8.3 ± 0.7%); no difference between groups	↓ area under the OGTT curve for insulin and glucose following RT relative to control, $P < 0.05$; ↔ in fasting blood glucose, fasting insulin, or BMI
Ishii et al. (52)	17: 9 RT and 8 control subjects/NRCT	Five times/week for 4–6 weeks	9 exercises, intensity 40–50% 1 RM; upper body: 2 sets of 10 repetitions, lower body: 2 sets of 20 repetitions; <60 s rest between sets	↑ glucose disposal rate with RT, $P < 0.05$; ↔ in A1C with RT (9.6 ± 2.8 to 7.6 ± 1.3%); ↔ in A1C in control (8.8 ± 2.1 to 7.6 ± 1.9%)	↔ body composition; ↔ in BMI; ↔ in $V\text{o}_{2\text{peak}}$
Dunstan et al. (43)	36: 19 RT+WL and 17 WL-only subjects/RCT	Three times/week for 6 months	9 exercises; weeks 1 and 2, intensity 50–60% 1 RM; weeks 3–26, intensity goal 75–80% 1 RM; 3 sets of 8–10 repetitions; 90–120 s rest between sets	↓ in A1C with RT+WL (1.2 ± 0.9%, $P < 0.01$); ↔ in A1C with WL only (0.4 ± 0.8%)	↓ in body mass and waist circumference in both groups, $P < 0.01$; ↓ in fat mass in both groups, $P < 0.01$; ↔ in HDL, LDL, fasting blood glucose, or triglycerides
Castaneda et al. (40)	62: 31 RT and 31 control subjects/RCT	Three times/week for 16 weeks	5 exercises; weeks 1–8, intensity 60–80% 1 RM; weeks 10–14, intensity 70–80% 1 RM; weeks 9 and 15, intensity reduced by 10%; 3 sets of 8 repetitions	↓ in A1C with RT (8.7 ± 0.3 to 7.6 ± 0.2%, $P < 0.01$); ↔ in A1C in control (8.4 ± 0.3 to 8.3 ± 0.5%)	↑ in muscle glycogen with RT and a ↓ with control, $P < 0.05$; ↑ in lean mass with RT, $P < 0.05$; ↓ systolic blood pressure with RT; ↔ in HDL, LDL, fasting blood glucose, triglycerides, or BMI
Baldi et al. (38)	18: 9 RT and 9 control subjects/RCT	Three times/week for 10 weeks	10 exercises, intensity 10 RM upper body, 15 RM lower body; intensity progressively increased by 5%; 60 s rest between sets	↓ in A1C with RT (8.9 ± 0.8 to 8.4 ± 0.6%, $P = 0.057$); ↔ in A1C in control (8.5 ± 0.7 to 8.4 ± 0.6%)	↓ in fasting insulin and fasting blood glucose with RT, $P < 0.05$; ↔ in 2-h glucose or insulin; ↑ in fat-free mass with RT, $P < 0.05$
Fennichia et al. (47)	7 RT (type 2 diabetic) and 8 RT (healthy control) subjects/NRCT	Three times/week for 6 weeks	8 exercises, intensity 8–12 RM; 3 sets of 8–12 repetitions; 90 s rest between sets	↓ area under the OGTT curve for glucose after acute RT, $P < 0.01$; ↔ area under the OGTT curve for glucose after chronic RT; A1C not reported	↓ in fat mass in type 2 diabetic but not in healthy control subjects $P < 0.01$; ↑ fat-free mass in healthy control but not type 2 diabetic subjects $P < 0.01$; ↔ in BMI
Ibanez et al. (51)	9/NTD	Two times/week for 16 weeks	7–8 exercises; weeks 1–8, intensity 50–70% 1 RM, 3–4 sets of 10–15 repetitions; weeks 9–16, intensity 70–80% 1 RM, 3–5 sets of 5–6 repetitions; 20% of training: 30–50% 1 RM, 6–8 repetitions, 3–4 sets as rapidly as possible	↓ in intra-abdominal adipose tissue with RT (10.3%, $P < 0.001$); ↓ in abdominal subcutaneous fat with RT (11.2%, $P < 0.001$); ↔ in A1C with RT (6.2 ± 0.9 to 6.2 ± 0.9%)	↑ in insulin sensitivity with RT (46.3%, $P < 0.01$); ↓ fasting blood glucose; ↔ in BMI
Combined resistance training and aerobic training trials					
Maiorana et al. (53,54)	16/randomize cross-over design	Three times/week for 8 weeks	Circuit = 7 resistance exercises, 8 cycling stations, and 5 min walking; RT intensity 55–65% 1 RM for 15 repetitions; AT intensity 70–85% HR_{peak}; 45 s exercise and 15 s rest; progressed up to 3 circuits	↓ A1C with RT + AT (8.5 ± 0.4 to 7.9 ± 0.3%, $P < 0.05$); ↑ flow-mediated dilation; ↑ forearm blood flow ratio to acetylcholine ($P < 0.05$)	↓ fasting blood glucose and percent body fat with RT+AT, $P < 0.05$; ↔ in HDL, LDL, triglycerides, or BMI; ↑ $V\text{o}_{2\text{peak}}$ with RT+AT, $P < 0.05$

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Table 1—*Continued*

Source	*n*/design	Study length	Exercise prescription	Primary findings	Secondary findings
Cuff et al. (22)	28: 9 AT, 10 RT+AT, and 9 control subjects/RCT	Three times/week for 16 weeks	RT = 5 exercises; RT intensity not reported; 2 sets of 12 repetitions; AT: many different modes; AT intensity 60–75% HRR; duration not reported	Greater glucose disposal rate in RT+AT than AT, $P < 0.05$; ↔ in A1C in any group	↓ in abdominal visceral and subcutaneous adipose tissue ($P < 0.05$) in both groups; ↑ in muscle density greater in RT+AT than RT ($P < 0.05$)
Tomakidis et al. (56)	9 RT+AT subjects/NTD	Two times/week for 4 months	RT = 6 exercises; RT intensity 60% 1 RM; 3 sets of 12 repetitions; AT: walking/jogging; AT intensity 70–85% HR_{peak}; duration 40–45 min	↓ area under the OGTT curve for insulin ($P < 0.05$) and glucose ($P < 0.01$); ↓ A1C with RT+AT (7.7 ± 1.7 to 6.9 ± 1.0%, $P < 0.01$)	↔ in fasting insulin; ↔ in BMI
McGavock et al. (55)	24: 17 RT+AT and 7 control subjects/NRCT	Three times/week for 10 weeks	RT = 7 exercises; RT intensity 50–70% 1 RM; 3 sets of 10–15 repetitions; AT: cycling; AT intensity 65–75% HRR; duration 30–55 min	↑ in large artery compliance ($P < 0.05$); ↔ in A1C (6.6 ± 0.9 to 6.4 ± 0.6%)	↑ in Vo_{2peak} ($P < 0.05$); ↔ in insulin sensitivity; ↔ in HDL, LDL, fasting blood glucose, triglycerides, or BMI
Balducci et al. (39)	120: 62 RT+AT and 58 control subjects/RCT	Three times/week for 1 year	RT = 6 exercises; RT intensity 40–60% 1 RM; 3 sets of 12 repetitions; AT: many different modes; AT intensity 40–80% HRR; duration 30 min	↓ A1C with RT+AT (8.3 ± 1.7 to 7.1 ± 1.2%)*	↑ in HDL*; ↓ in LDL, fasting blood glucose, triglycerides, BMI, and fat mass*; ↓ in waist circumference*; ↓ in systolic blood pressure ($P < 0.04$) and diastolic blood pressure*; ↑ in fat-free mass*

AT, aerobic training; CWT, circuit weight training; HR_{peak}, heart rate peak; HRR, heart rate reserve; NRCT, non-RCT; NTD, nontrial design; OGTT, oral glucose tolerance test; PME, preceived maximal exertion; RM, repetition maximum; RT, resistance training; Vo_{2peak}, peak O_2 consumption. *$P < 0.0001$.

that moderate-intensity circuit resistance training significantly reduced the plasma insulin response to glucose ingestion during an oral glucose tolerance test, which led to improved self-monitored blood glucose measurements. Complementary to these findings, Ishii et al. (52) demonstrated that the glucose disposal rate measured by hyperinsulinemic-euglycemic clamp increased 48% with high-volume (five times per week) moderate-intensity resistance training performed for 4–6 weeks compared with a nonexercising control. However, no statistical change in A1C was observed (9.6 ± 2.8 to 7.6 ± 1.3%). The nonsignificant change in A1C reported in these two studies can likely be explained by the short duration of training used, which may not have allowed the full effect of the intervention on A1C to occur (52). Further explanation of these findings may also be due to an insufficient intensity and/or volume of resistance training to optimally change body composition.

These earlier studies were supported by two larger RCTs (40,43) that investigated the effects of a longer, higher-intensity resistance training intervention. Dunstan et al. (43) randomized 36 overweight older men and women (aged 60–80 years) into a progressive resistance training plus moderate weight loss (RT+WL) group or a moderate weight loss control group who only performed flexibility exercise (WL). A greater reduction in A1C was observed for the RT+WL group (1.2%) compared with weight loss alone (0.4%, $P < 0.01$). This finding was observed without any difference between groups for waist circumference or total fat mass. However, the WL-only group tended to lose lean body mass (0.4 kg), while the RT+WL group tended to increase lean body mass (0.5 kg).

Similar findings were also reported by Castenada et al. (40), who randomized 62 older adults to either supervised high-intensity progressive resistance training or a nonexercising control group for 4 months. In the resistance training group, A1C was reduced from 8.7 to 7.6%, while muscle glycogen storage increased by 31%. In contrast, the control group showed no change in A1C and a 23% reduction in muscle glycogen storage. Systolic blood pressure was also reduced in the resistance training group, but there were no differences in other cardiovascular risk factors such as HDL, LDL, and total cholesterol levels. Body weight remained stable in both groups, but there was a mean increase in lean tissue mass of 1.2 kg in the resistance training group that significantly correlated with the improvement in A1C ($r = -0.35$, $P = 0.03$). A secondary, but still important, finding was that diabetes medication was reduced for 72% of individuals in the resistance-trained group compared with 3% in the control group, while 7 and 42% of individuals increased their medication in each group, respectively. Although these findings clearly support the benefits of resistance training for lowering A1C, it should be noted that the mean physical activity levels of those in the resistance training group significantly increased during the study and may have contributed to the promising improvements observed.

In another more recent RCT, Baldi et al. (38) utilized a more moderate–intensity program that emphasized muscle hypertrophy (i.e., 10–15 repetitions to failure with short rest periods) and reported that resistance training significantly reduced A1C (8.9 ± 0.8 to 8.4 ± 0.6%, $P = 0.057$), fasting glucose, and insulin. There was also a significant 6.9% increase in fat mass in the control group and a 3.5% increase in fat-free mass in the resistance training group. Again, the increase in fat-free mass inversely correlated with changes in A1C ($r = -0.63$) and fasting glucose ($r = -0.66$), suggesting that more moderate–intensity programs can also affect muscle size and improve glycemic control.

The common finding that increases in skeletal muscle mass are related to decreases in A1C (38,40,46) supports the hypothesis that resistance training improves glycemic control by augmenting the skeletal muscle storage of glucose.

However, whether this is due to an increase in muscle size and/or qualitative aspects of muscle function has not been fully elucidated. Interestingly, insulin sensitivity has been reported to occur without a change in lean body mass (52), which suggests that qualitative improvements in skeletal muscle function play a role in the resistance training–induced improvements in insulin sensitivity. In support of this postulate, Holten et al. (49) demonstrated that one-legged resistance training enhanced insulin action in skeletal muscle in individuals with type 2 diabetes, which was likely independent of increased muscle mass. Additionally, the protein content of GLUT4, insulin receptor, glycogen synthase, and protein kinase B-α/β as well as total glycogen synthase activity were enhanced. In concert, these findings demonstrate improvement in the insulin signaling pathway and in the regulation of insulin-mediated GLUT4 translocation, which would at least partially explain the improved insulin sensitivity with resistance training.

As abdominal adiposity has also been linked to insulin resistance (57,58), it is possible that resistance training reduces visceral adiposity and improves insulin sensitivity. Ibanez et al. (51) reported that resistance training reduced visceral and subcutaneous fat by 10.3 and 11.2%, respectively, while insulin sensitivity increased by 46.3%. Interestingly, no significant relationship between the improvements in insulin sensitivity and the losses in either visceral or subcutaneous fat were found. Although care should be taken in interpreting these findings due to the small sample size and uncontrolled study design, it would appear that reductions in visceral and subcutaneous adiposity with resistance training might not be the mechanism responsible for the improved insulin sensitivity with this type of training.

Considering the available evidence, it appears that resistance training could be an effective intervention to help improve glycemic control. Furthermore, the effect of resistance training on A1C reported in the three RCTs (38,40,43) is comparable with that reported with aerobic exercise (1). Indeed, a recent RCT (42) that randomized 43 individuals with type 2 diabetes to either resistance training or aerobic training (AT group) for 4 months, reported that A1C was significantly reduced with resistance training (8.3 ± 1.7 to 7.1 ± 0.2%, $P < 0.001$) but not aerobic training (7.7 ± 0.3 to 7.4 ± 0.3%, $P > 0.05$). The change in A1C between the RT and AT groups was also significant ($P = 0.04$). Furthermore, fasting blood glucose and insulin resistance were reduced and lipid profile improved with resistance training but not aerobic training. These findings highlight the potential benefits of resistance training for this population. However, with the substantial evidence that now supports both resistance training and aerobic training for managing glucose homeostasis, it is possible that a combination of the two exercise modalities may be the optimal intervention.

Combined resistance and aerobic training

Whether combined resistance and aerobic training would have a synergistic effect on glycemic control in individuals with type 2 diabetes has been addressed by a number of studies (22,39,53–56). Maiorana et al. (53) used a prospective randomized cross-over protocol to demonstrate that circuit training, with combined stations of aerobic and resistance training, significantly improved both peak oxygen consumption and muscular strength. Additionally, A1C (8.5 ± 0.4 to 7.9 ± 0.3%) and fasting glucose were significantly reduced. Data from the same sample in a later publication (54) also showed that combined training enhanced conduit and resistance vessel endothelial function, as demonstrated by improvements in brachial artery flow-mediated dilation and an improvement in the forearm blood flow ratio to acetylcholine. Although these data (53,54) supplied evidence for the beneficial use of combined training, the cross-over design only allowed comparison between combined training and a nonexercising control.

In a more recent RCT, Cuff et al. (22) randomized 28 obese postmenopausal women with type 2 diabetes into either a control, an AT-only, or an aerobic training plus resistance training (AT+RT) group. While both training regimes resulted in significant reductions in body weight and abdominal adiposity, only the AT+RT improved insulin sensitivity and glucose disposal. The AT+RT group also exhibited a significantly greater increase in muscle density than the AT-only group. Improved glucose disposal with training was significantly related to the reductions in abdominal subcutaneous ($r = -0.64$) and visceral ($r = -0.32$) adipose tissue as well as area of normal-density muscle ($r = 0.52$). These findings are in contrast to the aforementioned study by Ibanez et al. (51) and would suggest that improved glucose clearance was a result of both reduced visceral adiposity as well as enhanced muscle quality. However, whether this is an effect of the resistance or aerobic training or a combination of the two still needs to be elucidated.

Further support for a combined approach comes from the largest published study (39) performed in this area to date ($n = 120$). Balducci et al. (39) demonstrated that low- to moderate-intensity resistance training combined with moderate aerobic exercise three times per week for 1 year significantly improved metabolic and lipid profiles as well as adiposity and blood pressure. More specifically, compared with a nonexercising comparison group, A1C was significantly reduced from 8.3 to 7.1%, fat mass was reduced 2.5%, while fat-free mass was increased 0.4 kg. Additionally, fasting blood glucose, LDL cholesterol, and total cholesterol were significantly reduced, while HDL cholesterol was increased. The findings of this study (39) demonstrate more global improvements in cardiovascular risk factors than has currently been reported in resistance training alone and, in combination with the marked improvement in A1C, highlights the potential benefits of combined training for individuals with type 2 diabetes. Furthermore, these findings also identify that longer-duration, more moderate resistance training may be as beneficial as short-term high-intensity programs for maintaining glucose homeostasis and reducing cardiovascular risk factors. However, some caution is warranted in interpreting these results, as study participants were allowed to self-select whether they wanted to be in the exercise or nonexercise groups, and Balducci et al. (39) does not report the between-group changes observed postintervention.

Although previous studies (22,39) have provided evidence for the benefit of combined training versus aerobic training or a nonexercising control group, it is still unknown whether combined training offers any additional benefits over resistance training alone. The need still exists for a large RCT that examines each training regime separately, and in combination, to provide more definitive evidence in this area.

Optimal resistance training prescription for type 2 diabetes

Recent recommendations in the ADA technical review (9) support the American College of Sports Medicine guidelines (59) that resistance training be included as an essential component of a well-balanced physical activity program for those with type 2 diabetes who do not have contraindications to exercise. Specifically, the American College of Sports Medicine advocates that resistance training should be performed on at least 2 days per week, with a minimum of 8–10 exercises involving the major muscle groups for 10–15 repetitions to near fatigue. The American College of Sports Medicine further highlights that increased intensity or additional volume of training could produce greater benefits and may be appropriate for some individuals (59). Similarly, Sigal et al. (9) recommends that resistance training should be performed with all the major muscle groups, three times a week, progressing to 8–10 repetitions at a weight that cannot be lifted >8–10 times. The primary difference between these two prescriptions is the higher intensity recommended for all individuals by the ADA, which is in light of recent reports suggesting that high-intensity resistance training is both feasible and appropriate for older individuals with type 2 diabetes (9).

The recommendation from the ADA is predominantly based on two RCTs (40,43) demonstrating that high-intensity resistance training improves A1C, whereas studies using lower intensities have not found consistent improvements in this parameter (50,52). As mentioned above, this may be more an issue of study length than exercise intensity. However, the aforementioned study by Balducci et al. (39) demonstrated that even low levels of resistance training (40–50% 1 repetition maximum) in combination with moderate aerobic exercise was sufficient to improve A1C to a similar extent to high-intensity resistance training (40) and also reduced a number of cardiovascular risk factors. Therefore, there is a need for research that can identify the optimal prescription of resistance training to induce benefits in skeletal muscle adaptation and control of glucose homeostasis. However, current data advocate that if individuals can be encouraged to make a lifestyle change that incorporates long-term resistance training into their daily routine, then resistance training is likely to be beneficial for improving glycemic control even at more moderate intensities.

FUTURE RESEARCH CONSIDERATIONS FOR IMPLEMENTING RESISTANCE TRAINING AT THE POPULATION LEVEL

— It is evident that research is now required that not only documents the benefits of resistance training but also identifies practical and economical ways to implement resistance training at the individual and population levels. The need for a population-based approach is most apparent when considering the risk to this population if resistance training is not performed. Population attributable risk is the incidence of a disease that is attributable to being exposed to a risk factor (i.e., not performing resistance training) (60). Although we currently cannot calculate a true population attributable risk for the risk of not performing resistance training in the diabetic population, we can extrapolate the population attributable risk concept with existing published results to demonstrate the impact of this behavior on reducing diabetes-related complications at the population level. Based on the estimated criterion that a 0.6% absolute reduction in A1C can reduce the risk of microvascular complications by as much as 32% (61), along with the reported efficacy of the three aforementioned RCTs (38,40,43) that report a mean 0.9% reduction in A1C, this translates to a 48% reduction of microvascular complications. Further, it is has been reported from a North American population of type 2 diabetic individuals ($n = 1{,}193$) that 88% do not perform resistance training activities (62). Therefore, even if population-level resistance training strategies were modestly successful, their effects according to Rose's (63) population theorem, would have significant impact on reducing the burden of this disease at the population level.

Despite the importance of increasing activity levels in the type 2 diabetic population, there are numerous challenges regarding the feasibility of implementing this form of exercise. From a practical standpoint, performing resistance training without initial instruction can be daunting to the inexperienced and/or elderly individual, and few are likely to adopt resistance training without supervision. Existing studies use resource-intensive, supervised, one-to-one individual and clinically based approaches, and to date, we are unaware of any that offer practical, sustainable, economically viable strategies to implement resistance training as a viable physical activity option. The following addresses the lack of literature in this area and identifies needed research in this domain.

Long-term impact

No known research has been conducted on the long-term efficacy, retention, and adherence of resistance training programs in this population, and there is a need for research to examine these questions in both clinical and nonclinical settings. It may be that longer duration, low- to moderate-intensity resistance training programs that utilize slower progression may be more beneficial than shorter, more intensive programs.

Settings and delivery modes

There may be inherent difficulties in implementing resistance training programs that normally require supervision to unsupervised settings. Studies are required to explore the feasibility of unsupervised programs from initial instruction to graduated independence and the sequencing, amount, and intensity of booster/refresher sessions needed. Future research is also required to guide the success of such programs to ensure the feasibility, safety, and ultimate attitudinal, behavioral, and clinical efficacy of such strategies.

To date, little is known about the effectiveness or feasibility of home-based training, speciality gymnasiums, community-based education classes and programs, or the combinations of the above, with and without clinical supervision. The only known study in this area (44) demonstrated that after a 6-month supervised gymnasium-based resistance training program, home-based resistance training was effective for maintaining muscle strength but was inadequate for maintaining improvements seen in glycemic control during supervised training (43). Adherence to the home-based resistance training program was significantly lower (73%) compared with that previously observed for the supervised gymnasium-based training (88%). Similarly, training volume decreased by 52% from that previous being performed under supervision, and this reduction was primarily attributable to a 62% reduction in training intensity ($P < 0.001$). Further research is required to understand the types, combinations, temporal sequencing, and feasibility dimensions of such potential approaches. Furthermore, it would appear that a number of community gymnasiums and public fitness centers may have a significant role to play in providing education and supervision to individuals with type 2 diabetes. Typically, these centers have focused on young athletic individuals; however, with an aging population and a growing prevalence of type 2 diabetes (11), it may be appropriate for these facilities to readdress their target market. There would appear to be a need for specialized trainers and centers that can assist people with type 2 diabetes to incorporate resistance training safely and effectively into their daily routine.

Research examining modes of delivery (e.g., combinations of print and computer-/web-based media and telephone counseling, separately and in combination) for resistance training to the above strategies must also be explored for their feasibility, cost, and efficacy. Such approaches are feasible for population-based approaches, as they have the potential to reach a large number of individuals in a relatively cost-effective manner and have shown some success for the general and diabetic populations in the promotion of aerobic physical activity (62,64,65). Further, tailored messages appear to be more efficacious than generic mass education approaches for producing change across various health behaviors, including physical activity, in population studies (66,67). However, research to date has focused on aerobic exercise, and it cannot be assumed that the results of such approaches are applicable to resistance training, given the technical nature of this behavior. Research is needed to examine the feasibility and efficacy of such modes of delivery specifically for resistance training in this population.

Cost-effectiveness

Costs of resistance training programs for both efficacy and effectiveness studies on this population have yet to be determined. Therefore, there is an imperative need to conduct cost-effectiveness analyses on intervention strategies, comparing the incremental direct costs of the interventions relative to the incremental gain in physical activity achieved within the program period. Costs must also be examined at the individual (e.g., equipment costs) and system (e.g., health care service delivery) levels in terms of long-term, economic feasibility.

The need for specific resistance training theory and measurement

There is a need for theoretically driven approaches. Despite the mode of intervention delivery, great potential exists in the utilization of social-cognitive theories to explain behavior change and drive interventions/programs for diabetic populations (68,69). Indeed, approaches that incorporate social-cognitive theories are shown to be more efficacious than atheoretical-based interventions in the general population (70). However, it is estimated that only 12% of diabetes education and behavioral research uses a theoretical base (69).

Theoretical models need to be tested in populations with type 2 diabetes to identify factors that can be operationalized to achieve behavior change (69,71). Identifying constructs and theories that can be used to increase the degree of behavior change in diabetic populations will enable interventions to be tailored more effectively and ultimately increase treatment efficacy for lifestyle behavioral change (66,69). Although recent studies provide some initial support for the application of social-cognitive theories among this population (i.e., self-efficacy is an important construct that facilitates aerobic physical activity behavior change [71,72]), these investigations have been relatively exploratory in nature (62). However, it is worth noting that social-cognitive theories have only been applied for the promotion of aerobic-type activities; no study to date has assessed the determinants of resistance training in this population. Indeed, there appears to be only one published study (73) that has explored resistance training correlates in a sample of healthy older individuals. It is crucial that the predictors of this behavior are understood so that they may be appropriately tailored in subsequent interventions (74).

Given that the items/scales from current instruments are focused on aerobic activity (72), they may not adequately reflect the relationship between the various social-cognitive constructs and resistance training when corresponding measures are applied to this modality. For example, perceived barriers, attitudes, and confidence toward an aerobic activity, such as walking, may be very different for resistance training. Testing theories/models with appropriate measures would enhance the ability of such theories to explain this behavior and guide interventions. As there is no information to date on the determinants of resistance training in those with type 2 diabetes, the first step to designing a successful resistance training intervention is to develop valid and reliable measures, specific for this mode of activity and population. These measures should then be used to assess the salient and strongest predictors of resistance training to guide interventions by operationalizing the appropriate theoretical constructs.

In addition to clinical markers, resistance training programs need to examine other important outcomes for the type 2 diabetic population. To date, research has not investigated the attitudinal, behavioral, and quality-of-life outcomes to resistance training. Further, researchers should be encouraged to specifically assess resistance training–related cognitions and behaviors with validated instruments in physical activity prevalence studies.

Models and frameworks

Such resistance training population-based interventions and programs ultimately need to be focused at multiple levels taking an ecological perspective. Ecological models recognize the role of the environment and the interrelationships within and between multiple environments or levels (75,76), allowing the examination of the interaction among singular dimensions of the individual (e.g., biomedical, attitudinal, behavioral) with these multiple components of one's context (i.e., social, organizational, community, public policy, and physical environments) (62). Ecological models consider the interrelationships between the individual and his/her environment, as well as interactions within and between the various ecological levels. Such models could therefore provide a framework through which the interaction of the singular dimensions of the individual with the multiple components of his/her life context can be examined for explaining and promoting resistance training.

There is a need to couch and institutionalize resistance training education and promotion strategies for public health authorities in a guiding framework. The RE-AIM framework has been applied in the evaluation of health behavior change interventions, specifically those that target physical activity (77) and diabetes (78,79). The framework is comprised of five evaluative components that describe the overall population-based impact of an intervention: reach, efficacy, adoption, implementation, and maintenance (78). The RE-AIM framework focuses on the overall population-based impact by placing emphasis on both internal and external validity while considering both individual and system level outcomes. The use of such a framework helps to prioritize public health issues as it impacts real-world settings, facilitating the translation of research into practice (78,80).

SUMMARY— There is now suggestive evidence supporting the use of resistance training for improving glycemic control and insulin sensitivity in type 2 diabetes. However, the majority of studies have used individually supervised training sessions, where participants have been advised on exercise technique, prescription, and suitable progression. The current evidence is that small resistance training efficacy studies may not have applicability or generalizability at the population level for those living with type 2 diabetes. There is now a definite need for larger, population-based efficacy and effectiveness studies that address the feasibility of resistance training on a broader level. Such research should be theoretically driven and should strive to be cost-effective, feasible in a variety of settings, and effective over the long term, while reaching a large proportion of the relevant population. For success, it is important that a coordinated interdisciplinary approach involving academics, governments, health care organizations, practitioners, and the public should be taken to promote resistance training behavior from the clinical to population-based settings.

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