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REVIEW

Exercise Interventions for Autistic People: An Integrative Review of Evidence from Clinical Trials

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Abstract

Purpose of Review This review integrates recent findings from randomized controlled clinical trial (RCT) research examining the impacts of physical exercise activities on various aspects and areas of functioning for autistic individuals.

Recent Findings Recent meta-analytic and clinical trials research indicates physical exercise intervention programs improve social and communication skills for autistic children and adolescents, improve executive functioning skills for autistic children, improve sleep-related behavior for autistic children and adolescents, and may be helpful for improving physical health for autistic children. There is very limited RCT research evidence on exercise intervention approaches or impacts for autistic adults, for autistic girls or women, for autistic people with co-occurring intellectual disability, and for reducing negative emotional symptoms (e.g., anxiety, depression) for any autistic population.

Summary The extant clinical trials research provides convincing, consistent evidence for positive impacts of physical exercise programs on multiple areas of functioning for autistic children and adolescents. Additional research is needed to determine and ensure potential impacts of physical exercise activity programs for important autistic sub-populations, including adults.

Keywords Physical activity · Autism · Quality of life · Randomized controlled clinical trials

Introduction

Physical exercise activity involves moving one's body through space, and the choice to engage in exercise can be influenced by a combination of interests, emotions, and perceived benefits, intersecting with availability and accessibility. Regular physical exercise has long been studied and recommended for the positive impacts it produces for improving physical health [1]. While the recommendation of the World Health Organization (WHO) is for 150 min of physical exercise activity each week, studies have demonstrated that some benefits can also be observed after smaller amounts of exercise [2]. Exercise interventions vary in delivery method and modality and can range from individual informational programs designed to encourage and promote physical exercise activity, to family group classes, to formal policy-implemented school-based physical education exercise activity programs [3, 4]. There are a number of well-documented, evidence-based positive outcomes resulting from exercise for the general population [5]. The focus of the current paper is to examine and review the evidence for impacts of physical exercise activity programs specifically for autistic people.

Regarding specific targets, physical exercise has been found to be effective for reducing core psychiatric symptoms, limiting negative impacts of co-occurring secondary psychiatric and medical conditions, and improving physical health for patients living with several different psychiatric disorders [e.g., 6]. For example, there is evidence for positive impacts of physical exercise for patients with schizophrenia [e.g., 7], alcohol use disorder [8], and anxiety and depressive disorders [9, 10]. Across these conditions, engaging in physical activity has been found to have a variety of positive impacts, and therefore shows significant potential

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to improve functioning and quality of life for people with a variety of psychiatric conditions [8, 11].

Exercise can often be recommended to target specific core features of psychiatric conditions that cause individuals significant difficulties and distress. For example, people with schizophrenia present with varied core experiences and symptoms, including positive symptoms (e.g., hallucinations, delusions), negative symptoms (e.g., social, emotional, communication), and cognitive impairment. Scheewe, Backx [12] found that cardiovascular fitness and strength training exercise twice per week significantly reduced impacts of both positive and negative symptoms for patients with schizophrenia, compared with occupational therapy. Additionally, a recent meta-analysis of clinical trials indicated that people with alcohol use issues who engaged in long-term exercise programs (8 to 24 weeks; light aerobic exercise, moderate aerobic exercise, or yoga) exhibited significant decreases in weekly alcohol consumption [13]. Furthermore, exercise has been perhaps most well-studied for its positive effects on the treatment of symptoms of anxiety and depression. For example, physical activity has been found to delay the onset of anxiety and depression [9]. Among the general population, aerobic exercise activity has also been demonstrated to improve attention, working memory, processing speed, and other executive functions, each and all of which can be impaired in those with a variety of mental health diagnoses, either as core symptoms or as co-occurring mental health symptoms or diagnoses [14].

Disturbances in, or barriers to, maintaining physical health also commonly accompany psychiatric conditions and can pose additional stressors and even a shortened lifespan for patients. Physical health conditions common amongst individuals with psychiatric disorders include weight gain, cardiovascular disease, and diabetes. Regular exercise can aid in mitigating negative physical health outcomes associated with psychiatric conditions. For example, physical activity plays an important role in treating physical health concerns associated with antipsychotic medication use for patients with schizophrenia, including obesity, diabetes, and metabolic syndrome [7]. Moreover, people with alcohol use disorders (AUDs) are often undertreated, and AUD is often accompanied by serious secondary health risks including diabetes and cardiovascular disease. It has even been theorized that it may be easier to change lifestyle habits for this population when the focus is on increasing physical exercise activities rather than limiting alcohol use [8]. Exercise interventions have also been examined as a means for improving physical health outcomes associated with depression, including weight gain and sleep disturbance [10].

It is very well-documented that autistic people experience difficulties and distress in areas related to their core autism traits, co-occurring psychiatric and medical conditions, and that they often experience challenges with their physical health and well-being. It is, therefore, critically important that we develop and establish an evidence-based understanding of the potential benefits of physical exercise activities for the autistic population. As described earlier, exercise interventions have been found to reduce social symptoms in patients with schizophrenia, for example, which suggests that exercise may also help reduce core social symptoms for autistic people. In terms of co-occurring psychiatric difficulties and conditions, many autistic people experience significant difficulties with executive functioning [e.g., 15], and generally have disproportionately higher rates of mental health concerns, including anxiety and depressive disorders [e.g., 16]. With regard to physical health, research indicates that autistic individuals experience increased rates of obesity, sedentary behavior, cardiovascular disease, and diabetes, among other physical health difficulties [17, 18].

Autism Physical Exercise Intervention Research

Several meta-analytic studies have recently been conducted on the impacts of exercise interventions on different domains and aspects of functioning in autistic children and adolescents. Huang, Du [19] conducted a relatively comprehensive meta-analysis on the effects of exercise interventions on autism core symptoms (including autism symptoms, communication difficulties, stereotyped behaviors), as well as co-occurring motor skills difficulties. A more recent, updated meta-analysis further assessed the impacts of exercise interventions on autism core symptoms, namely social communication difficulties [20]. In 2022, Monteiro, Da Silva [21] conducted an updated meta-analysis examining the impacts of exercise interventions on co-occurring motor skills difficulties in autistic children. Another meta-analysis was the first to focus specifically on the impacts of exercise on co-occurring executive functioning difficulties in autistic children and adolescents [22]. Finally, in 2024, Liang, Haegele [23] conducted the first meta-analysis examining the impacts of exercise on sleep difficulties in autistic children and adolescents.

The purpose of the current paper is to provide an overarching, integrative review, update, and analysis addressing current evidence-based knowledge regarding the impacts of physical exercise interventions for autistic people. As part of this review, the findings of each of the meta-analyses is considered and reviewed, along with more recent clinical trials. We review the impacts of physical exercise activities on autistic individuals according to the following three areas of functioning: Core Autism Symptoms, Co-Occurring Conditions, and Physical Health. In all cases, the strong emphasis will be on considering and reviewing evidence specifically from randomized controlled clinical trials as the base medical standard.

Physical Exercise Activity Intervention Effects on Core Autism Symptoms

Impacts of Physical Activity on Levels of Autism, Social Skills, and Communication Skills

Huang, Du [19] published a single article in which they conducted 5 separate meta-analyses directly examining the consistency of impacts of physical activity on autistic children and/or adolescents in different aspects of their functioning. Three of these meta-analyses relate to core social and communication symptoms (i.e., levels of autism symptoms, social interaction skills, communication skills), and one examined the core symptom of stereotyped behaviors (see Table 1). The meta-analysis of levels of autism symptoms included 4 clinical trials ($n = 179$) and indicated no significant effect of physical activity on level of autism symptoms (e.g., Childhood Autism Rating Scale; Autism Behavior Checklist). An additional meta-analysis within their paper examined impacts of physical activity on social interaction skills, included 3 clinical trials ($n = 197$), and indicated consistent positive impacts of physical activity on social interaction skills across studies of children and adolescents with autism (e.g., Social Cognition Subscales of Social Responsiveness Scale and Gillian Autism Rating Scale). Their third meta-analysis relevant to core symptoms focused on assessing the impacts of physical activity on communication, included 4 clinical trials ($n = 240$), and indicated significant improvements in communication skills across studies of children and adolescents with autism (e.g., Social Communication Subscale of Social Responsiveness Scale and Communication Subscale of Gillian Autism Rating Scale). In 2023, Jia and colleagues reported an updated meta-analysis examining the impacts of physical activity on communication skills in children and adolescents with autism [20]. This meta-analysis included 14 clinical trials ($n = 460$), with results indicating that physical activities consistently improve communication skills, with a medium effects size.

Despite the null finding in Huang, Du [19] exercise and levels of autism symptoms meta-analysis seemingly conflicting with the positive impacts on social and communication skills found in their other meta-analyses and Jia, Guo [20] meta-analysis, this can perhaps best be explained by differences in the focus of the measurements. The studies included in the "levels of autism" analysis generally used more broad and more wide-ranging measures of autism symptoms, such as the Childhood Autism Rating Scales (CARS) and the Autism Behavior Checklist (ABC) [19]. On the other hand, the three social and communication skills-focused meta-analyses utilized more targeted measures focused within the specific domain of functioning, such as the Social Responsiveness Scale (SRS) or relevant subscales of a broader assessment (e.g., Social and Communication Subscales of the Gilliam Autism Rating Scales; GARS). Moreover, the broader measures of autism symptoms (e.g., CARS; ABC) used in the "levels of autism" meta-analysis studies also often included measures of autism symptoms not reflective of social and communication skills, such as restricted interests and repetitive behaviors. Therefore, the finding of consistent positive impacts of physical activities on social skills and communication skills for autistic people is not inconsistent with the finding that physical activities do not reduce the overall level of autism [27, 28]. Instead, this pattern of findings suggests that physical activity effectively improves both social and communication skills for autistic children and adolescents in ways that are measurable, meaningful, and important; however, the degree to which an autistic person's social and communication skills are improved may not consistently change their overall levels of autism symptoms in ways that would impact their overall diagnosis or their broader autism symptom severity (e.g., as indexed by broad autism assessments such as the CARS or the ABC).

Recent clinical trials examining the impacts of physical activity on levels of autism symptoms, social skills, and/or communication skills which were not included in the meta-analyses described above include the following. Sotoodeh, Arabameri [24] utilized a pre-/post-test design with a treatment-as-usual control group study to examine the impact of an 8-week yoga program on experimentally blinded, parent-reported severity of autism symptoms using the Autism Treatment Evaluation Checklist (ATEC) with autistic children aged 7- to 15-years (IQ > 80). They reported significant improvement in the experimental group compared with the control group for three of the subscales of the ATEC (i.e., Sociability, Cognitive and Sensory Awareness, and Health and Physical Behavior), but not the Speech and Language Subscale. These findings provide further support for positive, and socially valid (i.e., experimentally blinded parent report), impacts of physical activity on social functioning for autistic children and adolescents.

An additional randomized crossover control study ($n = 29$) was designed to determine whether single session aerobic exercise on a stationary bike would improve facial recognition abilities in autistic children, ages 7- 12 years [25]. Results indicated that face recognition performance decreased from pre- to post-test in the exercise condition compared with a sedentary (i.e., video watching) control condition. This study is an interesting initial exploratory investigation of potential lower-level neural and perceptual mechanisms which might underlie positive impacts of physical exercise on social functioning in autistic children; however, the study measures were administered after only one single session of physical activity while previous studies have observed positive social skills impacts only after

Table 1 Impacts of physical exercise activities on autism core symptoms. Meta-analytic studies of clinical trials and representative recent clinical trials examining the impacts of physical activity interventions on core autism symptoms for autistic people

Study	Participants	Interventions	Measures	Summary of Results
Meta-Analysis on Intervention Effects of Physical Activities on Children and Adolescents with Autism Huang et al., 2020 [19]	4 studies ($N=179$)	Studies: - Xu et al. 2018 - Wu 2017 - Yang et al. 2016 - Yang et al. 2017	META-ANALYSIS: LEVELS OF AUTISM	Combined statistics had no statistical significance
Meta-Analysis on Intervention Effects of Physical Activities on Children and Adolescents with Autism Huang et al., 2020 [19]	3 studies ($n=197$)	Studies: - Pan et al. 2015 - Bahrami et al. 2013 - Vardi et al. 2017	META-ANALYSIS: SOCIAL INTERACTION ABILITY	In autistic children and adolescents, physical activity significantly improved social interaction ability ($z=3.95$, $p<0.0001$)
Meta-Analysis on Intervention Effects of Physical Activities on Children and Adolescents with Autism Huang et al., 2020 [19]	4 studies ($n=240$)	Studies: - Movahedi et al. 2015 - Pan et al. 2015 - Wu 2017 - Yang et al. 2016	META-ANALYSIS: COMMUNICATION	Significant improvement in communication ability in children and adolescents with autism ($z=2.25$, $p=0.2$)
The effect of physical exercise on disordered social communication in individuals with Autism Spectrum disorder: a systematic review and meta-analysis of randomized controlled trials Jia et al., 2023 [20]	14 studies, ($n=460$)	Studies: - Cia et al. 2020 - Cia et al. 2020 - Movahedi et al. 2013 - Xu et al. 2019 - Wang et al. 2020 - Chan et al. 2013 - Bahrami et al. 2016 - Phung 2021 - Zanobini & Solari, 2019 - Koch et al. 2015 - Yang et al. 2021 - Najafabadi et al. 2018 - Haghighi et al. 2022 - Aithal et al. 2021	META-ANALYSIS: COMMUNICATION	Meta-analysis results indicated that physical exercise can improve disordered communication in individuals with ASD with a medium effect size (0.45)
Effectiveness of yoga training program on the severity of autism Sotoodeh et al., 2017 [24]	+29 participants +7—15 (mean 11.22, SD 2.91) +using DSM-5 diagnostic criteria +Gender not reported +Race & Ethnicity not reported +SES not reported	Between group design +Yoga training intervention +Control group	+Autism treatment evaluation checklist (ATEC) given at baseline and the end of the intervention and filled out by experimentally blinded parents or caregivers	+Study indicates the yoga treatment program reduced autism symptomatology as measured by experimentally blinded parent reported ATEC (3 out of 4 sub-sections)
A randomized cross-over trial investigating the neurocognitive effects of acute exercise on face recognition in children with autism spectrum disorder Ludyga et al., 2023 [25]	+29 participants +Aged 7—12 +APA DSM-5 criteria as of 2022 +Gender not reported +Race & Ethnicity not reported +SES not reported	+Exercise → moderate exercise on a cycling ergometer for 20 min, watched a video of what it would look like from a cyclists' perspective +Control → sat on cycling ergometer for 20 min, watched the same video as Exercise group	+Face specific M170 ERP +Eye Tracking using an eye tracker machine (pupil size) +face processing (compared to instruments) behavioral task	+Face recognition decreased from pre- to post-test in the exercise condition compared with the control condition +The exercise condition was associated with reduced change in amplitude of the N170 face processing component

Table 1 (continued)

Study	Participants	Interventions	Measures	Summary of Results
Meta-Analysis on Intervention Effects of Physical Activities on Children and Adolescents with Autism Huang et al., 2020 [19]	2 studies ($n = 146$)	Studies: - Movahedi et al. 2012 - Pan et al. 2015	META-ANALYSIS: STEREOTYPED BEHAVIOR	Combined statistics had no statistical significance
Choosing an Appropriate Physical Exercise to Reduce Stereotypic Behavior in Children with Autism Spectrum Disorders: A Nonrandomized Crossover Study Tse et al., 2018 [26]	+30 participants +9- 12 years old +ASD diagnosis from a physician based on the Diagnostic and Statistical Manual of Mental Disorders, 5th edition +22 male and eight female participants +Race & Ethnicity not reported +SES not reported	Crossover study design +A- B design with one month break in between +Control = story time +Intervention = ball tapping	+Gilliam Autism Rating Scale- 3rd edition (only repetitive behavior scale was used)	+Ball tapping significantly reduced hand flapping stereotypic behavior but not body rocking stereotypic behavior, indicating that exercise activity reduced stereotypic behavior that matched the physical characteristics of that stereotypic behavior

multiple sessions. Moreover, this study observed negative impacts on face perception without measuring social skills. Taken together, the relevance of the findings of this study to our understanding of social skills improvements are currently unclear. Although we applaud the researchers for wanting to better understand mechanisms underlying physical activity related improvements in social functioning, we would encourage future research in this area to focus on producing further-reaching clinical impacts that improve quality of life for autistic people, versus lower-level mechanisms, at this point in time.

Impacts of Physical Activity on Restricted and Stereotyped Behaviors

As indicated earlier, Huang, Du [19] also conducted a meta-analysis examining the impacts of physical activity on stereotyped behaviors for autistic individuals. This meta-analysis only included 2 clinical trials ($n = 146$) and indicated no positive impacts of physical exercise for reducing stereotyped behaviors in autistic children and adolescents (see Table 1).

One study not included in that meta-analysis was an experimentally controlled cross-over design which investigated whether or not matching exercise activity type to specific stereotyped behavior actions reduced the frequency of stereotyped behaviors in autistic children aged 9- to 12-years [26] (see Table 1). The study findings indicated that a ball tapping intervention was effective for reducing hand flapping stereotypic behavior but not body rocking. This preliminary finding suggests that physical exercise activities may be effective in reducing stereotyped behavior if the specific topography of the targeted behavior is the same as the physical activity used in the intervention. However, the experimental design used in the study does not control for the possibility that hand flapping behaviors were reduced because the physical activity intervention specifically tired out their arms. Therefore, it is important to conduct follow-up studies in order to replicate and extend this initial finding.

In 2022, researchers conducted a school-based randomized controlled clinical trial examining the impacts of a morning jogging intervention (2 times per week) compared with an education as usual control [29]. They reported improvements from pre-intervention to post-intervention for the jogging group on the Repetitive Behavior Subscale of the GARS. However, this effect was not significantly different for the jogging versus control groups, and this study had several experimental and practical limitations that are discussed below. At this point in time, there is insufficient evidence from clinical trials to support consistent positive impacts of physical exercise activities on restricted and stereotyped behaviors for autistic people.

Physical Exercise Activity Intervention Effects on Co-Occurring Conditions

Co-occurring psychological and physical difficulties which commonly occur for autistic people can have serious negative impacts on both their day-to-day functioning and quality of life. Here, we review the clinical trials evidence base for positive impacts of physical exercise activities on several co-occurring conditions which are common in autistic people.

Impacts of Physical Activity on Executive Functioning

Deficits and difficulties in executive functioning, including but not limited to diagnosis of Attention Deficit Hyperactivity Disorder (ADHD), are among the most common co-occurring psychological conditions for autistic people. Moreover, they are also one of the most studied in terms of clinical trials in relation to physical activity interventions. A recent meta-analysis directly examined the consistency of impacts of physical activity on executive functioning abilities in autistic individuals [22]. This meta-analysis included 7 randomized controlled clinical trials and randomized crossover clinical trials designs ($n = 254$). Results indicated consistent small to moderate positive impacts of physical activity on executive functioning skills overall across studies of autistic children, with follow-up analyses indicating consistent positive effects for inhibitory control and cognitive flexibility but not for working memory (see Table 2).

In 2021, Tse and colleagues conducted a three-arm randomized controlled clinical trial that was not included in the aforementioned meta-analysis [30]. In this study, 62 autistic children were randomized to 2 weeks of learning to ride a bicycle ($n = 22$), stationary cycling ($n = 20$), or wait-list control ($n = 20$). Significant statistical interactions were observed in 4 out of 6 measures of executive functioning (planning task, flexibility task, 2 of 3 working memory tasks, and 0 of 1 inhibition task) in the learning to ride a bicycle condition, compared with the other two conditions. The results of this study suggest that cognitive engagement in a physical activity task is valuable for improving executive functioning skills for autistic children. At the same time, the failure to find improvements in executive functioning in the stationary cycling condition overall, or compared with the wait-list control condition, seems generally inconsistent with the meta-analytic findings [22]. This is particularly true given that the level of intensity of the bicycle and stationary cycling intervention conditions was relatively high at 5 times per week [30]. However, one notable difference between this study and the majority of studies included in the meta-analysis is that those studies were generally of somewhat longer duration (e.g., 12 weeks) and at a lower intensity (e.g., 3 times per week) [22]. Future studies are needed to further our understanding of the relative roles of physical activity with more versus less cognitive engagement, as well as the role of exercise intervention duration and intensity in producing positive outcomes [23, 40].

An additional follow-up three-armed randomized controlled clinical trial was designed to examine the impacts of the same learning how to ride a bicycle group ($n = 23$), stationary cycling group ($n = 19$), and a walking control group ($n = 22$) on executive functioning and self-regulation [33]. Learning how to ride a bicycle produced significant improvements over the other two conditions for executive functioning, and learning how to ride a bicycle and stationary cycling produced improved self-regulation over walking. The findings of this study provide further clinical trials evidence for the positive impacts of physical activity on executive functioning for autistic children, and also provide additional evidence that the level of cognitive load required during an exercise intervention activity impacts the types of effects the intervention produces.

Liang, Li [22] meta-analysis documents the efficacy of physical activity interventions for producing improvements in executive functioning skills specifically for the autistic child and adolescent population, with the exception of working memory skills. The current evidence, however, yields small to moderate effects, indicating that there is likely room for further development and improved understanding of the factors which moderate both the consistency and the degree of impacts. For example, future research might focus on the impacts of different types and different intensities of physical activity intervention programs, as well as the duration / longevity of the improvements in executive functioning across time (e.g., hours, days). Furthermore, while executive functioning research has established a strong understanding of underlying cognitive mechanisms which can be measured in relatively intricate detail using button-pressing and reaction time tasks (e.g., Stroop task, go no-go task), it is critical that future research is designed to further determine and document positive impacts on broader measures which reflect consistent, measurable, and meaningful longer-term improvement in real-world functioning. These might include but, not be limited to, measures such as the Behavior Rating Inventory of Executive Functions (BRIEF), and measures of adaptive functioning and/or quality of life [33, 41]. For such studies, it will also be important to maintain strong experimental control, through experimental masking/blinding of informants, and to ensure that the intervention durations and intensities are sufficient to produce the deeper and broader impacts being measured in order to reduce the likelihood of clinical trial failure resulting from limited clinical power.

Table 2 Impacts of physical exercise activities on common co-occurring conditions. Meta-analytic studies of clinical trials and representative recent clinical trials examining the impacts of physical activity interventions on common co-occurring psychiatric and medical conditions for autistic people

Study	Participants	Interventions	Measures	Summary of Results
Executive Function				
The Effects of Exercise Interventions on Executive Functions in Children and Adolescents with Autism Spectrum Disorder: A Systematic Review and Meta-analysis Liang et al., 2022 [22]	7 studies, ($N=300$)	Studies: - Chan et al. 2013 - Pan et al. 2017 - Phung & Goldberg, 2019 - Greco 2020 - Greco & De Ronzi 2020 - Rafiei Milajerdi et al. 2021 - Rafiei Milajerdi et al. 2021	META-ANALYSIS: EXECUTIVE FUNCTIONING	A small—moderate effect size ($g=0.342$) was found for overall executive functioning in children with ASD
Improving executive function of children with Autism Spectrum Disorder through cycling skill acquisition Tse et al., 2021 [30]	+62 participants +Mean age 9.89 ± 1.53 +mild—moderate ASD (Level 1–2 support) +50 male, 12 females +Race & ethnicity not reported +SES not reported	Between group design +learning to ride a bicycle ($n=22$) +stationary cycling ($n=20$) +control—no exercise changes to regular amount ($n=20$)	+Computerized tower of London (TOL) +Corsi block tapping task (CBTT [31]) +Forward digit span (FDS) and backward digit span (BDS) tests +The Stroop Color and Word Test (SCWT [32]) +Computerized Go/No-go (GNG) task	+Significant improvement in executive functioning in the learning to ride a bike condition compared to the control condition and the stationary cycling condition
The relationships among executive functions, self-regulation, and physical exercise in children with autism spectrum disorder Tse et al., 2024 [33]	+64 participants +8–12 years old +mild to moderate ASD +12 female participants 52 male participants +Race & Ethnicity not reported +SES not reported	+Learning to ride a bike intervention, two week intervention with biweekly 6o minute classes +Stationary cycling intervention, two weeks of biweekly 60 min classes +Active control, 20 min walking with caregiver daily	+Computerized tower of london (TOL) task +Forward digit span (FDS) task +Backward digit span (BDS) task +Corsi block tapping task (CBTT) +The Stroop Color and Word Test (SCWT) +Computerized Go/No-go (GNG) task	+Significant improvements in TOL raw scores from T1 to T2 for the learning to ride a bike intervention group but not the other groups +From T1 to T2 the control group and learning to ride a bike groups showed significant increase in BDS +From T1 to T2 the learning to ride a bike group showed significant increase in CBTT scores +On the SCWT the learning to bike group had significantly lower scores than the other groups at T2. Additionally the learning to bike group had a decrease in SCWT scores while the other groups scores remained the same +GNG FA error was significantly smaller at T2 with a reduction from T1 in the learning to ride a bike group, but not in the other groups

Table 2 (continued)

Study	Participants	Interventions	Measures	Summary of Results
Effects of therapeutic recreation on adults with ASD and ID: a preliminary randomized control trial Garcia-Villamisar et al., 2017 [34]	+ 37 participants + Mean age for intervention = 31.84 (SD 6.07) Mean age for waitlist control = 35.00 (SD 6.36) + 12 females, 25 males + ASD, most participants had limited spoken language + Race and ethnicity not reported + SES not reported	+ TR-EF Intervention = 200 1 h sessions conducted five times a week. Activities to improve working memory, cognitive flexibility, and inhibition + Wait list control	+ Autism Spectrum Disorders—Diagnosis for Adults (ASD-DA) + Autism Spectrum Disorders—Comorbidity for Adults (ASD-CA) + Dysexecutive Questionnaire (DEX) + Personal Well-Being Index—Intellectual Disability (PWI-ID Third Ed) + Vineland Adaptive Behaviour Scales-Classroom Form (VABS) + Matson Evaluation of Social Skills for Persons with Severe Retardation (MESSIER) + Cambridge Neuropsychological Test Automated Battery (CANTAB)	+ Executive functioning improved from pretest to post test in the intervention group compared to the control group + There were no statistically significant group differences at post test in terms of inhibition, ASD-DA, the Vineland, or on the MESSIER + Statistically significant improvement in personal well-being in the intervention group compared to the control group at post test
Evaluating the effects of a yoga-based program integrated with third-wave cognitive behavioral therapy components on self-regulation in children on the autism spectrum: A pilot randomized controlled trial Tanksale et al., 2021 [31]	+ 61 participants + Ages 8–12 + Verified ASD Diagnosis + 22 girls. 39 boys + Race and ethnicity not reported + SES not reported	+ Intervention group = a six week yoga intervention with elements of third wave Cognitive Behavioral therapy included + Waitlist control group	Preliminary measures: + WASI-II + ADOS-2 + CASD Parent reported outcomes: + The Behavior Rating Inventory of Executive Function–Second Edition + Children's Sleep Habits Questionnaire + Anxiety Scale for Children–Autism Spectrum Disorder—parent version + Goal Attainment Scale Child reported outcomes: + Emotion Awareness Questionnaire + Anxiety Scale for Children–Autism Spectrum Disorder—self-report	+ The global executive composite score (overall EF) estimated marginal means (corrected averages) went down for the intervention condition but stayed the same for the waitlist control + Post intervention there were between group differences for sleep anxiety and bedtime resistance subscales and the intervention group had more disordered breathing + Post intervention there were group differences in verbal sharing of emotions post-intervention and follow up as well as in willingness to understand one's emotions + Except for the performance anxiety subscale at follow-up there were not statistically significant group differences in anxiety measures post intervention

Table 2 (continued)

Study	Participants	Interventions	Measures	Summary of Results
Anxiety and Emotional Regulation				
The effects of a physical exercise program, LEGOR and Minecraft activities on anxiety in underserved children with autism spectrum disorder Lo et al., 2023 [35]	+ 148 participants + 6–12 years old + ASD Diagnosis within two years and anxiety as measured on the SCARED (total score > 25) or the CBCL (> 93rd percentile) + Gender no reported + Families recruited were Latino and rural families + Race & Ethnicity not reported + SES not reported	+ Control = Sedentary activity (LEGO/Minecraft) for 45 min up to 3 times a week for eight consecutive weeks + Intervention = exercise intervention with trained instructor. Sessions were 40–50-min up to 3 times a week for 8 consecutive weeks	Primary outcome measure: CBCL DSM-5 anxiety subscale Secondary outcome measures: + SCARED + The Child's Sleep Habits Questionnaire (CSHQ) + Salivary cortisol levels	+ CBCL DSM-5 and SCARED showed improvement at weeks 3, 6, and eight in both groups with no significant difference between groups + In the physical exercise intervention group CBCL DSM-5 anxiety scores decreased at weeks 12 and 16 compared to baseline + During weeks 6 and 8 sleep also showed improvement for the exercise intervention group + No significant changes in salivary cortisol or differences in it between groups
Effects of a Gamified, Behavior Change Technique-Based Mobile App on Increasing Physical Activity and Reducing Anxiety in Adults With Autism Spectrum Disorder: Feasibility Randomized Controlled Trial Lee et al., 2022 [36]	+ 24 participants + Adults = > 18 + ASD and medical diagnosis of anxiety or self-identification of experiencing anxiety symptoms for the past 3 or more months + 15 female, 9 male + Race & Ethnicity not reported + SES not reported	+ Google Fit Intervention = Physical activity tracking platform with hearts as a rewarded + PuzzleWalk Intervention = physical activity tracking system that is gamified to reward physical activity	+ App use via self report + The Beck Anxiety Inventory (BAI) + time-specific and type of anxiety trigger questions + Daily walking steps + PA intensity + Sedentary time	+ Puzzle Walk intervention group spent significantly longer on the app compared to the Google Fit intervention group + Anxiety unfavorably linked with increase in physical activity + Anxiety unfavorably linked with decreases in sedentary time after intervention
Preliminary efficacy of occupational therapy in an equine environment for youth with autism spectrum disorder Peters et al., 2021 [37]	+ 21 participants + ages 6—13 + ASD diagnosis + 5 female, 16 male + 5 Hispanic/Latino participants + SES Reported in means for the two groups	+ Intervention = OT^{ee} HORSPLAY horse occupational therapy intervention + Control = garden based occupational therapy intervention	+ Goal Attainment Scaling (GAS) + Parent reported Aberrant Behavior Checklist-Community (ABC-C) + Parent reported Social Responsiveness Scale, Second Edition (SRS-2) + Parent reported Pediatric Evaluation of Disability Inventory Computer Adaptive Test, Autism Spectrum Disorder Module (PEDI-CAT ASD) + Hair cortisol content (HCC)	+ OT^{ee} HORSPLAY intervention showed improvements in social motivation and irritability, but no significant differences between intervention and waitlist control + No significant results for hair cortisol content, hyperactivity, social communication, in the mobility domain, in the social/cognitive domain, and in the daily activities or responsibility domains of the PEDICAT-ASD

Table 2 (continued)

Study	Participants	Interventions	Measures	Summary of Results
Evaluating the effects of a yoga-based program integrated with third-wave cognitive behavioral therapy components on self-regulation in children on the autism spectrum: A pilot randomized controlled trial Tanksale et al., 2021 [31]	+ 61 Participants + Ages 8–12 + Verified ASD Diagnosis + 22 girls. 39 boys + Race and ethnicity not reported + SES not reported	+ Intervention group = a six week yoga intervention with elements of third wave Cognitive Behavioral therapy included + Waitlist control group	Preliminary measures: + WASI-II + ADOS-2 + CASD Parent reported outcomes: + The Behavior Rating Inventory of Executive Function–Second Edition + Children's Sleep Habits Questionnaire + Anxiety Scale for Children–Autism Spectrum Disorder—parent version + Goal Attainment Scale Child reported outcomes: + Emotion Awareness Questionnaire + Anxiety Scale for Children–Autism Spectrum Disorder—self-report	+ The global executive composite score (overall EF) estimated marginal means (corrected averages) went down for the intervention condition but stayed the same for the waitlist control + Post intervention there were between group differences for sleep anxiety and bedtime resistance subscales and the intervention group had more disordered breathing + Post intervention there were group differences in verbal sharing of emotions post-intervention and follow up as well as in willingness to understand one's emotions + Except for the performance anxiety subscale at follow-up there were not statistically significant group differences in anxiety measures post intervention
Brief Report: Impact of a Physical Exercise Intervention on Emotion Regulation and Behavioral Functioning in Children with Autism Spectrum Disorder Tse, 2020 [38]	+ 27 participants + Age 8 −12 + ASD + Gender not reported + Race & Ethnicity not reported + SES not reported	Between group design + Exercise—12 week jogging intervention (15) + Control (12)	+ The Emotion Regulation Checklist (ERC, Shields and Cicchetti 1998) + CBCL	+ No significant interaction found for the ECR-LN subscale + Significant improvement from T1 to T2 in the intervention group for the ECR-ER subscale + No significant interaction for internal behavior section + Significant reduction form T1 to T2 in external behavior composite in intervention group + Significant reduction in total problem T-scores between T1 and T2 for the intervention group
Sleep Outcomes				
The impact of the physical activity intervention on sleep in children and adolescents with autism spectrum disorder: A systematic review and meta-analysis Liang et al., 2024 [23]	8 studies (N = 617)	Studies: + Ansari, et al., 2021 + Adib et al., 2021 + Gehricke et al., 2022 + NaraSiNgharao et al., 2017 + Tanksale et al., 2021 + Toscano et al., 2022] + Tse et al., 2019 + Tse et al., 2022	META-ANALYSIS	+ Physical Activity interventions have a positive effect on improving general sleep problems + Evidence may also suggest effects of improving night awakenings, sleep resistance, sleep duration, and sleep efficiency compared to no intervention

Table 2 (continued)

Study	Participants	Interventions	Measures	Summary of Results
Effects of exercise on sleep, melatonin level, and behavioral functioning in children with autism Tse et al., 2022 [29]	+55 participants +8—12 years old +ASD Diagnosis +8 girls, 47 boys +Race/ethnicity not reported +SES not reported	Between group design +Intervention group = 12 weeks of biweekly 30 min morning jogging sessions outdoors +control group	+Actigraphy assessments +Sleep efficiency +Wake after sleep onset +Sleep duration +Sleep log +Sleep efficiency +Sleep duration +Melatonin levels +Twenty-four-hour +First morning urinary	+The intervention group's sleep efficiency significantly increased from baseline to post intervention +The intervention groups wake after sleep onset decreased from baseline to post intervention +Compared to the control group participants in the intervention group had longer sleep duration +No significant differences in the Sleep log measures +Statistically higher levels of melatonin in the intervention group post intervention
Motor				
Meta-Analysis on Intervention Effects of Physical Activities on Children and Adolescents with Autism Huang et al., 2020 [19]	4 studies ($n = 172$)	Studies: - Pan et al. 2015 - Lourenco 2015 - Chu et al. 2016 - Azari et al. 2019	META-ANALYSIS: MOTOR SKILLS	Combined statistics had no statistical significance
The Effect of Physical Activity on Motor Skills of Children with Autism Spectrum Disorder: A Meta-Analysis Monteiro et al., 2022 [21]	4 studies ($N = 90$)	Studies: - Sarabazadeh et al. 2019 - Pan et al. 2016 - Hassani et al. 2020 - Arabi et al. 2019	META-ANALYSIS: MOTOR	No statistically significant findings
The Effects of Aquatic Versus Kata Techniques Training on Static and Dynamic Balance in Children with Autism Spectrum Disorder Ansari et al., 2020 [32]	+30 participants +8–14 years old +DSM5 ASD diagnosis +All male participants +Race & Ethnicity not reported +SES not reported	Between group +Karate (10) +Aquatic training (10) +Control group (10)	+Modified stork test +Walking heel to toe test	+Statistically significant improvement in both static and dynamic balance for both karate and aquatic training interventions compared to the control group

Table 2 (continued)

Study	Participants	Interventions	Measures	Summary of Results
Efficacy of Motor Interventions on Functional Performance Among Preschool Children With Autism Spectrum Disorder: A Pilot Randomized Controlled Trial Jin et al., 2023 [39]	+ 13 participants + Preschool aged 4–5 years old + APA 2013 ASD diagnosis & symptom severity o from mild to severe (mean score 34.3) + Gender not reported + Race & ethnicity not reported + SES not reported	+ MOTION–ASD + CO–EXC programs + for both interventions, eight, weekly ninety minute sessions with a 1:1 pre trained provider took place (researchers also observed sessions)	+ CARS-2 + TONI–4 + MABC–2 + BOT–2, Brief Form + Vineland Adaptive Behavior Scales–Third Edition	+ Significantly greater improvements on Vineland-3 motor domain and BOT-2-BF manual coordination for the MOTION-ASD group compared to the CO-EXEC group + point score for the total motor skills, BOT-2-BF fine manual control and body coordination, and amps motor skills and process skills showed significant improvement for both groups + Many of the motor improvements were maintained at the four week follow up

Impacts of Physical Activity on Anxiety and Emotional Functioning and Regulation

As described earlier, extensive research has documented that exercise programs can improve emotional functioning and regulation across a variety of populations, including symptoms of anxiety and depression. Extensive research has also documented elevated rates of anxiety and depression symptoms and diagnosis in the autistic population [16]. Despite this, there is, unfortunately, very limited clinical trials research on physical exercise's potential to improve anxiety or other emotion-related symptoms or experiences for autistic people. Moreover, the results of the extant clinical trials do not provide consistent positive evidence for impacts of physical exercise interventions on anxiety and/or emotional symptoms for autistic individuals (see Table 2). In a systematic review of the research on the impacts of physical activity interventions on anxiety for autistic people, 4 randomized controlled clinical trials were identified [42]. We discuss each of these studies, here, along with one other relevant and recent clinical trial.

In 2023, Lo, Lowery [35] conducted a randomized controlled clinical trial ($n = 148$) examining the impacts of an 8-week physical exercise activity intervention compared with a sedentary activity control on parent-reported and child-reported child anxiety, as well as cortisol levels, for 6- to 12-year old autistic children. The findings of this study were reductions in parent-reported anxiety across both conditions from pre-training to post-training, with no group interaction effects. This study can therefore be considered a null trial, producing no experimental evidence for the physical activity intervention program reducing anxiety symptoms or cortisol levels compared with the sedentary control condition.

Another randomized controlled clinical trial ($n = 24$) examined and compared two different app-supported physical activity intervention programs, the Puzzlewalk app and the Google Fit app, for reducing anxiety symptoms for autistic adults [36]. Data were collected 4-weeks and 8-weeks into the participants' use of these interventions. Results indicated no significant improvements in anxiety for either participant group. These findings can also be considered a failed clinical trial, producing no experimental evidence for either intervention program reducing anxiety symptoms.

In 2022, Peters, Wood [37] conducted a randomized controlled clinical trial ($n = 24$) examining the impacts of an equine therapy intervention program (OTee HORSPLAY) compared with a waitlist control for 6- to 13-year-old autistic children. Of relevance to anxiety and emotion regulation, participants in the intervention condition exhibited significantly reduced irritability from pre-intervention to post-intervention. However, there was no statistical interaction between time (pre-/post-intervention) and group

(intervention/control). Therefore, this study also does not provide clear or convincing evidence for positive impacts of physical activities on anxiety for autistic individuals.

Researchers conducted a randomized controlled clinical trial ($n = 61$) examining the impacts of a 6-week yoga program integrated with cognitive behavioral therapy components on self-regulation for 8- to 12-year-old autistic children [31]. Outcomes included child-reported emotional functioning and anxiety. Participants in the intervention group self-reported improved verbal sharing of emotions, improved analysis of emotions, and reduced performance anxiety, compared with waitlist control participants. The findings of this study should be interpreted with caution due to the absence of objective measures or experimental masking for the autistic participants, as well as some limitations to the statistical control for the analyses. However, these are among the first positive clinical trials evidence for the potential for a physical activity intervention program to reduce emotion-related symptoms and anxiety for autistic individuals.

In another study relevant to emotional functioning and regulation, Tse and colleagues [Tse and colleagues39] conducted a small randomized controlled clinical trial ($n = 27$) comparing 12 weeks of jogging ($n = 15$) to a treatment as usual control condition ($n = 12$). Parent reports (not masked) indicated significant improvement in the emotion regulation subscale of the Emotion Regulation Checklist as well as significant reduction in behavioral problems on the Child Behavior Checklist, when compared with the control group [33, 38]. The findings of this study are also preliminary due to both the small sample size and the reliance of the study measures on reporting from parents who were not masked to their child's experimental condition. It is critically important for the autistic population that additional, higher quality, and full-scale randomized controlled clinical trials research be conducted on the impacts of physical exercise interventions on anxiety and emotional functioning and regulation for autistic people.

Impacts of Physical Activity on Sleep

A recent meta-analysis examined the impacts of physical exercise activity interventions on sleep for autistic children and adolescents [23]. This meta-analysis included 8 clinical trials ($n = 654$) and determined that physical activity interventions had consistent, large positive effects on parent reported sleep problems, night awakenings, sleep resistance, and sleep duration, as well as actigraph accelerometer measured sleep efficiency. A strength of this literature includes studies which have employed ecologically valid parent reports measures of sleep-related behaviors in coordination with objective measures, including actigraph accelerometer data and/or sleep-related biological marker data (e.g., sleep-relevant inflammatory cytokines, melatonin) [29, 43]. Additional strengths of this literature include that most of the studies have examined impacts of exercise intervention programs which are community-based (e.g., in schools), and that a number of the studies are of reasonably long duration (e.g., 8- to 12-weeks). This being said, the clinical trials research on this topic is limited by relatively small sample sizes.

Impacts of Physical Activity on Motor Skills

In their 2020 paper involving multiple meta-analyses, Huang and colleagues reported a meta-analysis directly examining the consistency of impacts of physical activity on motor skills in autistic individuals [19]. This meta-analysis included 4 clinical trials ($n = 172$), and indicated no consistent positive impacts of physical activity on motor skills across studies of autistic children and adolescents (see Table 2). In 2022, Monteiro and colleagues conducted an updated meta-analysis which assessed the impacts of physical activity on motor skills specifically for autistic children [21]. This meta-analysis included 4 randomized controlled clinical trials ($n = 109$), and also indicated no evidence for consistent positive impacts of physical activity on motor skills of autistic children (see Table 2). Below, we consider some more recent and representative examples of clinical trials research on motor skills functioning which were not addressed in these meta-analytic reviews.

A three-armed randomized controlled clinical trial ($n = 30$) assigned autistic children to 10 weeks of karate exercise ($2\times$ per week, $n = 10$), aquatic exercise ($2\times$ per week, $n = 10$), or a no intervention control ($n = 30$) condition [32]. Intervention change measures were a measure of static balance (i.e., stork test, seconds) and a measure of dynamic balance (i.e., heel-to-talk line walking). Results indicated significantly improved balance across both static and dynamic balance for both intervention conditions relative to the control condition, as well as significantly improved overall balance for the karate exercise group over the aquatic exercise group. These findings provide support for balance-focused exercise training intervention improvements in static and dynamic balance for autistic children.

In 2023, Jin and colleagues conducted a pilot randomized controlled clinical trial examining and comparing the impacts of two different physical activity interventions designed to improve motor skills for autistic preschool children [39]. One intervention (MOTION-ASD) involved eight 90-min intervention sessions targeting postural control, locomotion, object manipulation, and manual dexterity. The other intervention (CO-EXC) involved eight 90-min intervention sessions targeting attention, impulse control, cognitive flexibility, working memory, and levels of physical activity. The MOTION-ASD intervention ($n = 7$) resulted

in significantly greater improvements in the Manual Coordination sub-test of the Bruininks-Oseretsky Test of Motor Proficiency (BOT-2) and the Motor Skills sub-domain of the Vineland Adaptive Behavior Scales, compared with the CO-EXC intervention ($n=6$). It is worth noting that the MOTION-ASD intervention was specifically designed to impact motor skills, whereas the CO-EXC intervention was designed to improve executive functioning [44], whereas the outcome measures for this study reflected motor skills and adaptive behavior [39]. The very small sample size and the large number ($n=13$) of statistical analyses run without reported control over statistical alpha levels for multiple comparisons render the reported findings as hard to interpret. Future studies with larger samples, an improved approach to statistical analysis, pre-intervention and post-intervention measures of motor functioning skills and executive functioning skills, and a third non-intervention comparison control condition appear warranted in this area.

Overall, the clinical trials research evidence is currently insufficient to suggest that physical activities improve motor skills for autistic children and/or adolescents. The research in this sub-field has generally been characterized by particularly small sample sizes, weaker experimental and statistical control, and more variable approaches to both intervention and research approaches. These limitations remain in recent and current work in this area. Research and publication activity is generally relatively high in this sub-area of physical activity intervention research for autism. However, larger sample sizes overall, larger sample sizes per intervention condition, more well-controlled controlled experimental designs and procedures, and improved statistical approaches will be necessary to properly determine whether or not physical activity intervention programs can improve motor skills for autistic individuals. Furthermore, it will likely be important for future research to identify and delineate sub-types of motor intervention approaches and/or motor intervention skills targets which may be more versus less effective and more versus less impacted for this population.

Physical Exercise Activity Intervention Effects on Physical Health

Despite well-documented associations of autism with reduced and impaired physical health, relatively limited clinical trials research has been conducted on the impacts of physical activity on physical health for the autistic population. In a systematic review of the literature from 1995 to 2016, Craig [45] identified 2 randomized controlled clinical trials relevant to physical health for autistic children [see also 46]. The first was a stratified block-randomized controlled clinical trial (n = 50), designed to examine the impacts of exercise-gaming (Wii "Mario and the Sonics at the Olympics"; see Table 3) [47]. The intervention was conducted in a community-based school setting in England, across the entire school year. The intervention group showed significantly larger degrees of positive change in measures of weight (i.e., BMI), cardiorespiratory fitness (i.e., VO2max), aerobic fitness (i.e., bleep test, shuttle run), and muscle strength (i.e., broad jump, sit-ups), but not flexibility. The authors of this study are commended on the fact that the autistic participants had co-occurring learning disability ranging from moderate to severe, which is a population for which there is less physical exercise activity intervention research [47].

The other RCT identified in Craig [45] review was conducted by Pan, Chu [48], and utilized a cross-over design in which 22 autistic boys aged 6- to 12-years were randomly assigned through paired stratification to receive 12 weeks of table tennis intervention provided in a university multi-purpose room immediately ($n=11$) or after 12 weeks ($n=11$) (see Table 3). The researchers included an objective, combined measure of physical strength and physical agility, and reported significant performance improvements on this measure specifically associated with the intervention period. Together, the findings of the studies by Dickinson and Place [47] and Pan, Chu [48] provide initial preliminary evidence that physical activity intervention programs may be helpful for improving physical health for autistic children.

Of relevance to clinical intervention practices and future research, Matheson, Drahota [50] conducted a pre-/post-training pilot study with no control group examining the feasibility and acceptability of a 16-week paired parent–child combined dietary and physical activity intervention program. The "TEAM UP" intervention, with modifications for autistic children, was delivered by the parent with guidance, direction, and support provided via weekly meetings with an advanced graduate student. The intervention targeted dietary recommendations / calorie reduction, physical activity (> 60 min per day), behavior change, and parenting strategies. Participants were between 5 and 14 years of age, and each had a BMI at or above the 85th percentile. Twenty parent–child pairs completed the baseline assessment and at least one treatment session. Three parent–child pairs dropped out of the study. Analyses focused on the remaining 17 children indicated significant reductions in BMI from pre-treatment to post-treatment (estimated 2.68 lbs weight loss). According to parent reports, children participating in this study increased their physical activity from an estimated 5.82 times per week to an estimated 8.53 times per week and increased their intake of vegetables from 10.2 servings per week to 11.75 servings per week. Finally, additional analyses focused on 16 parents who completed the study, and the study questionnaires indicated provided good evidence for intervention satisfaction, acceptability, and usefulness. The results of this pilot study are promising in that they provide

evidence for the acceptability and perceived usefulness by parents of a relatively broad and long-term physical health-focused intervention program. The results also suggest the possibility that this intervention program may have potential to produce direct positive impacts on physical health in overweight and/or obese autistic children. However, lack of a control group, the relatively small sample size, and other limitations to the experimental design and analyses mean that proper randomized controlled clinical trials will need to be conducted to draw any conclusions on the potential impacts of this intervention approach.

Overall Summary of Physical Exercise Activity Intervention Effects for Autistic People

In this integrative review of the exercise and autism clinical trials research literature, we have determined that physical exercise activities have consistent positive impacts on core social skills and communication skills for autistic children and adolescents. These positive impacts are measurable, meaningful, and socially valid; however, the interventions studied to date have not yet been shown to reduce the overall severity level of core autistic traits. We have also determined that physical exercise activities improve executive functioning skills for autistic children, specifically for inhibitory control and cognitive flexibility but not for working memory. Moreover, we have found that clinical trials research indicates that physical exercise activities improve sleep-related behaviors for autistic children. Finally, preliminary clinical trials research suggests that physical exercise activities may be helpful for improving physical health for autistic children. On the other hand, we have determined that there is currently insufficient clinical trials evidence to indicate that existing physical exercise interventions reduce repetitive or stereotyped behavior or improve motor skills for autistic people.

During this review, we have identified a critical gap in the extant literature, such that very few clinical trials have examined the ability of physical exercise to reduce negative emotional symptoms or increase positive affect or emotions for the autistic population. Furthermore, those that have been conducted have generally not been of high quality and have not produced positive evidence. Anxiety, depression, and emotion-related symptoms are among the most internally challenging and practically debilitating symptoms for many autistic people [51, 52]. As described at the beginning of this review, physical activity has been repeatedly shown to reduce negative emotional symptoms and improve positive affectivity across a variety of populations. Furthermore, research on other interventions designed to reduce anxiety and depressive symptoms has been limited [53], presents somewhat complicated delivery methods [e.g., 54], and have also been found to produce unique negative side effects [e.g., 55] for the autistic population. It is pivotally important for clinical trials research to properly determine whether or not and, if so, how, physical activity interventions can contribute to reducing anxiety, depression, and for improving emotion-related symptoms in general for the autistic population.

While the extant literature is strong enough to draw these conclusions at present, there are also a number of important and on-going limitations to the literature. For example, of the large number of RCTs conducted in this literature, only 2 focused on adults. Furthermore, with rare exceptions, participant sample sizes used in the clinical trials research literature to date have been small, with many studies using samples in the 20 to 30 participants range and some as low as 13 total participants. The literature is also limited in terms of participant diversity, including gender diversity (e.g., ~ 75% to 80% male samples), failure to even report participant race/ethnicity in the majority of cases, and failure to report socioeconomic status of the participating individuals or families in the majority of cases. The result of these serious limitations is that we currently have essentially no evidence-based understanding of the impacts of exercise interventions for autistic adults, for autistic girls or women, on gender diverse people, or on how race/ethnicity moderates or mediates the impacts of physical exercise activities. We also have very little to no evidence-based understanding for how variations in gender, race/ethnicity, and/or socioeconomic status affect accessibility and other aspects of participation in the various physical activity intervention programs that have been studied to date.

In addition to sociodemographic biases, the extant clinical trials literature on exercise and autism has often excluded autistic participants with co-occurring intellectual disability or those who are minimally speaking. While strict exclusion criteria can help researchers draw more definitive conclusions, studies which exclude participation in this way do not account for the heterogeneity amongst autistic peoples' presentations and thus, limits the generalizability of study findings [56] [57]. One important step towards practicing better inclusivity is to normalize reporting on cognitive and language functioning of study samples, to help document disparities in research [58]. Additionally, through implementation of direct measures of exercise participation (e.g., heart rate, time spent exercising scored from video) and enjoyment (e.g., positive affect scored from videos) and objective measures of symptom improvements (e.g., masked informant reports, actigraph accelerometer measurements, physiological or autonomic measurements), researchers can in fact properly develop and determine effective physical exercise intervention programs and determine their impacts in clinical trials specifically for autistic people with co-occurring intellectual disability and/or language impairment [59].

Table 3 Impacts of physical exercise activities on physical health. Studies of representative recent clinical trials examining the impacts of physical activity interventions on physical health for autistic people

Study	Participants	Interventions	Measures	Summary of Results
The Impact of a Computer-Based Activity Program on the Social Functioning of Children with Autistic Spectrum Disorder Dickinson & Place, 2014 [47]	+ 100 participants + ASD diagnosis and moderate to severe learning disability + ages 5—15 + 21 girls, 79 boys + Race and ethnicity not reported + SES not reported	+ Intervention group = standard physical intervention and Wii game Mario and Sonic at the Olympics + Control group = standard school physical education only	+ Body mass index + Bleep test + Standing long jump test + 10×5 m shuttle test + Partial curl up test + Sit and reach test + Flexibility + VO2 max	+ Control and intervention groups differed on board jump, bleep test, sit-up activities, flexibility, and shuttle run test at the start + Intervention group exhibited statistically significant improvements compared with the control group on all physical fitness measures except flexibility + The Intervention group had statistically significant improvement on all fitness measures and BMI
The impacts of physical activity intervention on physical and cognitive outcomes in children with autism spectrum disorder Pan et al., 2017 [48]	+ 22 participants + age 6—12 (9.08 ± 1.75) years old + DSM-IV-TR ASD diagnosis + all male participants + Race & ethnicity not reported + SES not reported	Between group crossover study (A → B & B → A) + Intervention = physical activity intervention + Control group = no intervention	+ Anthropometric measurements + BOT-2 → motor skill proficiency + computer version of the WCST → executive functioning	+ Both groups demonstrated significant improvements in motor skills and executive functioning when exposed to the intervention. Additionally Group A's (the first to receive these interventions) improvements lasted at least twelve weeks
Step It Up: Increasing Physical Activity for Adults With Autism Spectrum Disorder and Intellectual Disability Using Supported Self-Management and Fitbit Technology Savage et al., 2022 [49]	+ 40 participants + Ages 18—57 + Clinical ASD Diagnosis & IQ < 70 + 70.6% male + 61.11% White, 22.22% Multiracial, 16.67% Black or African American + SES not reported	+ Intervention = Fitbit and Step it Up intervention with coaches with weekly goal setting meetings and individualized exercise sessions + Control = fitbit but not Step it Up intervention	Primary outcomes: + Weekly step count via fitbit + BMI + Quality of Life questionnaire (QOL.Q)	+ Adjusting for baseline the intervention group participants took more weekly steps across the intervention than the control group + From baseline to post test on average the participants in the intervention group lost more weight + Quality of life scores were not statistically significantly different over time

Physical Activity Intervention Activities and Approaches for the Autistic Population

In light of the evidence-based positive impacts reported from physical exercise, it is also important to consider which different types of physical activities might be appropriate and effective for autistic individuals. Focusing on the intervention activities that have been implemented in studies reviewed in the current paper, these are incredibly varied. Examples include specifically Aerobic Exercise activities such as jogging, stationary cycling, and exercise-gaming. Examples also include specifically Motor and Focus exercise activities, such as yoga, Tai Chi, and training karate kata. Still other examples include physical activities described and defined more broadly as training, including basketball skill training, trampoline training, table tennis, and aquatic training activities. Several of these training programs appear to provide participants with skills-focused training, but with aerobic activity and/or motor and focus activity occurring variably within the training program. Finally, applied cognitive tasks are incorporated into physical exercise activities in some studies. For example, several studies have compared learning to ride a bicycle to stationary cycling [33].

While a number of studies have implemented physical activities in laboratory settings that are not reflective of real-world intervention contexts (i.e., efficacy trials), it is very notable that a relatively large number and percentage of the clinical trials have actually examined real-world interventions in context (i.e., effectiveness trials). For example, one moderately sized and longer-term RCT was conducted in schools in England, and produced broad positive physical health outcomes from an exercise-gaming intervention [47]. For another example, Tse and colleagues have published several clinical trials conducted in schools in Hong Kong, generally showing positive effects from different types of exercise interventions (e.g., basketball skill learning, [60]; morning jogging, [33]). Other studies have incorporated existing community-based service delivery program models, such as karate training studios or yoga studios; or created programming which could be relatively easily adapted to existing service delivery models. For an example of the latter, Pan, Chu [48] delivered a table tennis training intervention program to children in a university multipurpose room, which could relatively easily be adapted for delivery through a community center, an afterschool program, a clinic, or another community setting. Finally, Matheson, Drahota [50] delivered their autistic child physical activity intervention pilot program through a parent-focused delivery model, as part of a larger intervention program that addressed health more broadly (dietary, physical activity, behavior change). This program was implemented through each parent meeting weekly with a graduate student who provided guidance and support, but has potential to be extended more directly into the community through further experimental research development.

Integrating and Interpreting the Evidence with Real World Clinical Practice

Although a scientific research base is absolutely critical for determining and establishing the value and impacts of physical activity interventions on various aspects and domains of functioning, there is a prominent gap between how and where research is conducted and how and where autistic people receive their services at any point in time.

School-Day Physical Activity Programs

At present, most physical activity intervention programs are delivered through physical education programs operating within education systems [61, 62]. For the general population, these programs are naturally built into the child or adolescent's school day, and often focus on targeting motor skills [63]. For the autistic population, there are often barriers to their participation in these programs as they are designed and implemented for the general population. Therefore, it is important to collaborate with autistic children, adolescents, and/or their caregivers and service providers to determine the levels and types of physical activities that they are actually engaging in at school and, where possible, to put accommodations into place. This ultimately aims to increase the autistic individual's integration and engagement in school-based physical activities. Subsequently, this may include after school programs, such as formal high school team sports program participation, where appropriate.

Community-Based Physical Activity Programs

Alternative or supplemental opportunities for physical activity for autistic children, adolescents, and adults involve community-based programs. These include, but are not limited to, recreational sports team programs, recreational summer camps which include physical activities, and physical activity programs offered through community centers and private studios (e.g., yoga, martial arts). Currently, these programs vary tremendously regarding not only their overall suitability and/or appropriateness for some autistic individuals but also their adaptability for the integration and inclusion of autistic people across the spectrum. Therefore, identifying appropriately matched programs may require significant investigation, recommendations / referrals, and/or involve a challenging trial-and-error process for the individual and/or their family.

Individual and Family-Based Physical Activities

One of the most noteworthy aspects of physical activity as an intervention is its relative accessibility. As described in some detail above, beneficial physical activity can be as simple as going for an early morning jog, practicing yoga at home, or learning how to ride a bike from a parent or sibling. Although not yet directly studied in clinical trials for autistic individuals, other solo and family physical activities can include swimming laps in a pool, hiking, and weightlifting, among many others. Moreover, one key to physical activity patterns that improve physical and mental health is establishment of routine patterns of physical activity. Therefore, there seems to be great potential in providing psychoeducation about the positive impacts of physical activities on overall well-being. In turn, this may motivate autistic people to incorporate regular physical activities into their established routines.

Barriers to Engaging in Physical Activities

While it is important to consider the ways that people can engage in various types of physical exercise activities, it is also important to consider barriers to engaging in physical activities, and associated baseline habits and activity levels. Common barriers to physical activity amongst the general population include financial costs, lack of energy, and preference of other activities. These barriers are often further exacerbated for autistic people and/or their families [64]. For example, the high cost of some exercise activities can be a financial barrier, especially considering the high unemployment rates among autistic adults and the financial costs of specialist services and other needs for autistic children and adolescents. Additionally, sedentary activities can provide autistic individuals with more predictable routines in a familiar environment. Lastly, physical activity may expose individuals to unpleasant sensory experiences that they would rather avoid despite known positive impacts of exercise. In order to increase the appeal of exercise engagement, it is pivotal to consider, discuss, and address these and other potential barriers through collaboration with autistic people and/or their caregivers to identify physical activities which match the unique barriers, preferences, motivations, and opportunities for each autistic individual.

Perhaps the greatest barrier to developing a regular exercise regimen lies in difficulties with motivation. A recent systematic review uncovered how decreased feelings of autonomy, connectedness, and competence can drastically impact motivation [65]. In some cases, autistic individuals may feel less competent during exercise activities due to motor skill differences, or difficulty understanding activity instructions. Furthermore, a lack of relatedness to non-autistic peers or fears of exclusion can make engaging in group exercise activities feel daunting for some autistic people. Critically, autistic youth may feel as though structured physical activity does not present as an autonomy-supportive environment. In conjunction with previous suggestions to address other barriers, shared engagement and commitment to the process of identifying and developing supportive environments and adapting activities to meet autistic individuals' needs can help alleviate concerns or fears that hinder motivation.

Autistic self-advocates also need to be directly involved in both clinical development and research design. Increasingly, emphasis on autistic self-advocate involvement in research has been made, but there is still significant room for improvement. For example, only a limited number of studies having stakeholder involvement from the beginning of the research process [52]. It is vital in the push for autistic involvement in research for advocate involvement to occur both in setting priorities for future research as well as the initial designing and implementation of research projects. Research which has begun to explore autistic advocates' research priorities has found that autistic self-advocates, along with their families, place emphasis on research seeking to improve quality of life over research focusing on biological mechanisms and the biological causes of autism [52]. Research focusing on mental and physical health is a particularly high priority for autistic people [51, 52, 66]. Given physical and mental health's high priority status, research into exercise as an intervention for autistic people must have involvement at every step of the process. Participatory procedures ensure that this research is conducted with a focus on autistic people's priorities and allows self-advocates to lend their unique insights into the autistic experience to co-develop truly effective and truly accessible physical exercise activity intervention programs and truly impacting clinical trials research on this critically important topic.

Conclusions

Research designed to examine the impacts of physical exercise activities on various aspects and areas of functioning for autistic people has been on-going for decades. This has culminated into clinical trials research studies which have been conducted primarily across the past 1.5 decades. The clinical trials on this topic have often been completed with limitations in their experimental designs and procedures, and particularly their sample sizes. However, sufficient randomized controlled clinical trials have been conducted to date to produce a number of recent statistical meta-analytic studies examining the consistency of clinical impacts of physical exercise activities for autistic children and adolescents. The results of these meta-analytic studies and more recent randomized controlled clinical trials have documented a variety

of meaningful and measurable consistent positive impacts of physical exercise activity programs for autistic people. These include but are not limited to consistent positive impacts on core autism social and communication skills symptoms, and improved symptoms related to co-occurring conditions such as executive functioning and sleep difficulties. Preliminary clinical trials evidence further suggests the possibility that physical activity interventions may be helpful for improving physical health indicators such as lowering BMI, increasing strength and agility, and/or improving cardiorespiratory fitness for autistic children.

While recent research indicates clearly that there is now a convincing evidence base that engaging autistic individuals in physical exercise activity programs will improve their functioning, there remain significant barriers to ensuring access to and participation in such programs for this population. For example, while an impressive number of the clinical trials reviewed in this paper were conducted in community-based settings (e.g., schools, martial arts studios), the reality is that the majority of autistic individuals will not have access to the same types of autism-specialist and/or autism-integrated programs utilized in those studies. Furthermore, autistic people equally face many of the same motivational and other barriers that non-autistic people face when it comes to engaging in regular physical activity, in addition to some unique additional potential barriers such as increased social and financial burdens. Therefore, it is critically important that clinicians, educators, and other professionals work collaboratively with autistic people and their families to identify person-specific physical exercise programs and opportunities to achieve exercise activity levels that will produce positive effects for each individual.

Despite consistent evidence for positive impacts of physical exercise activities and programs for autistic people, there remain significant limitations to the literature. In particular, there is a clear need for more RCTs examining the impacts of physical exercise activities and programs on anxiety, depression, and other emotion-related symptoms, and on physical health. For the emotion-related symptoms, where initial small-scale studies have generally not produced positive results, there appears to be need for pilot RCTs to help establish feasible intervention programs and identify intervention outcome measures which show potential for use in full-scale RCTs. For physical health, preliminary initial RCT findings are generally positive and the need is primarily for more RCTs, including larger-scale RCTs conducted in community settings. The entire exercise and autism RCT literature is generally plagued by relatively small sample sizes and poor generalizability to the base demographics of the autistic population. It is absolutely critical that future research in this field make more diligent efforts to recruit and study sociodemographic subgroups of autistic people who are not properly represented in the current RCT literature, namely 1) adults, 2) girls, women and gender-diverse individuals, 3) racial and/or ethnic minorities, and 4) those from middle- to low-income families. Furthermore, it is essential for this field of research to leverage objective measures of activity and improvement in order to conduct RCTs for autistic people with co-occurring intellectual disability or language impairments. Finally, truly participatory clinical development and truly participatory research is pivotally important for developing interventions that autistic people can access, will use, and which will result in truly meaningful and important improvements in their functioning, experiences, and quality of life.

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Declarations

Competing Interests The authors declare no competing interests.

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