

Personalized, physiotherapist-guided exercise programs in juvenile idiopathic arthritis: home-based vs. immersive virtual reality (JiaFitXR)

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Abstract

Objective:

To compare the effects of two physiotherapist-guided, personalized, stepwise-adapted exercise interventions—a home-based program (HomeEX) and an immersive virtual reality (IVR) exergaming program (JiaFitXR)—on physical fitness, functional capacity, and physical activity in adolescents with juvenile idiopathic arthritis (JIA).

Methods:

This randomized controlled trial included 50 adolescents aged 13–18 years with JIA, randomly assigned (1:1) to HomeEX or JiaFitXR. Both programs targeted balance, strength, endurance, and agility, delivered twice weekly for eight weeks under physiotherapist supervision. Functional capacity (6-Minute Walk Test, Sit-to-Stand, Step-Up/Step-Down tests) and physical fitness (FitnessGram components, muscle strength, EMG activation, grip force) were assessed pre- and post-intervention by blinded physiotherapists. Analyses were performed using paired and independent t-tests and repeated-measures ANOVA, following the intention-to-treat principle.

Results:

Both physiotherapist-guided interventions significantly improved physical fitness, functional capacity, and daily activity ($p < 0.05$). Greater gains in 1-Minute Sit-to-Stand, Step-Up, and Step-Down tests, as well as in lower extremity endurance and neuromuscular activation, were observed in the JiaFitXR group ($p < 0.05$). The HomeEX group showed superior improvements in flexibility and upper extremity strength ($p < 0.05$). Step counts increased similarly in both groups, while perceived exertion remained stable throughout the program.

Conclusion:

Both physiotherapist-guided exercise approaches effectively enhanced physical and functional outcomes in adolescents with JIA. The IVR-based intervention provided additional benefits in lower extremity endurance and engagement, supporting its potential as an innovative and motivating adjunct to pediatric rheumatology rehabilitation.

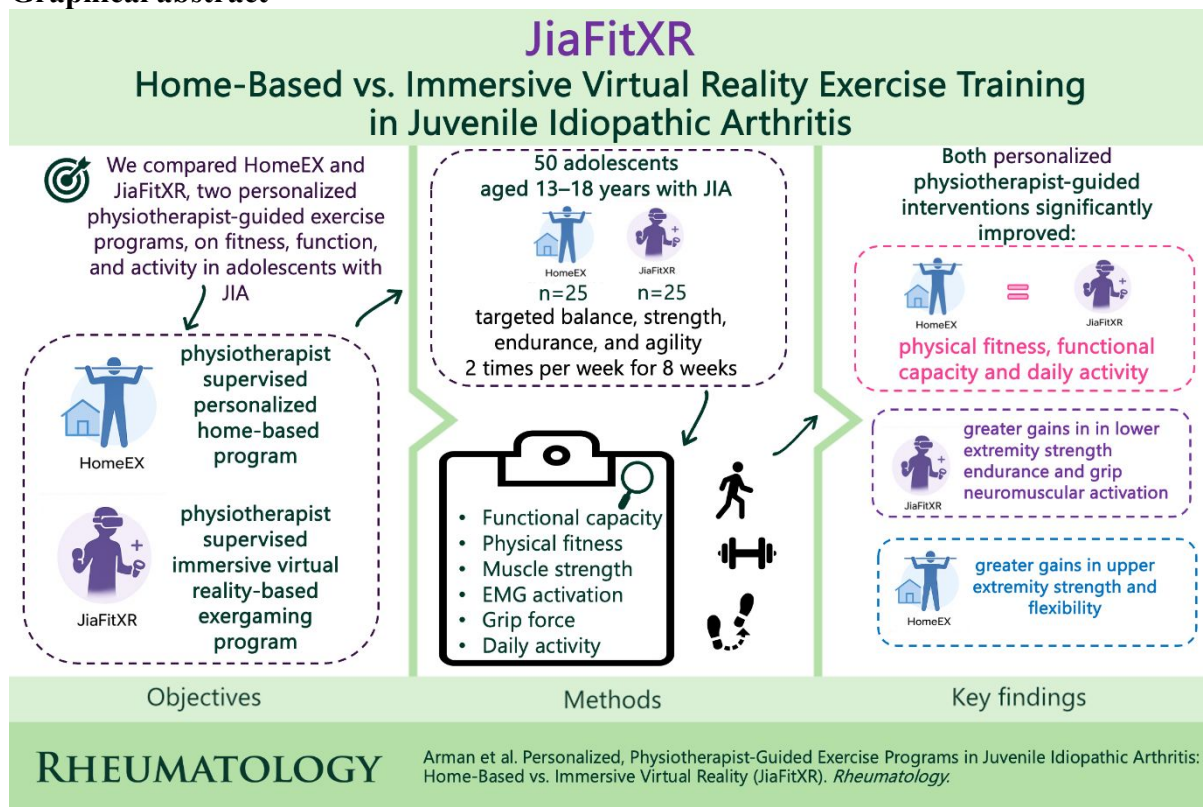
Clinical Trial registration: ClinicalTrials.gov; NCT06176846

Key Words: Virtual Reality, Exergaming, JIA, Physical Fitness, Functional Capacity

Key Messages

- Personalized immersive virtual reality exergaming improves lower-limb endurance, neuromuscular activation, and engagement in JIA.
- Personalized home-based exercise improves flexibility and upper-limb strength, providing an accessible rehabilitation option in JIA.
- Integrating immersive virtual reality into personalized care offers engaging and potentially beneficial outcomes in JIA.

Graphical abstract

**Introduction**

Juvenile idiopathic arthritis (JIA) is the most common chronic rheumatic disease in childhood. Persistent joint inflammation, pain, and limited mobility impair growth, psychosocial well-being, and long-term musculoskeletal health (1). Children and adolescents with JIA consistently demonstrate lower physical fitness, muscle strength, and functional capacity compared to their healthy peers, along with higher fatigue levels and reduced motivation to engage in physical activity (2,3). These limitations contribute to sedentary behaviors and reduced quality of life, underscoring the need for safe and engaging exercise interventions.

Structured exercise programs have been shown to be feasible and beneficial in children diagnosed with pediatric rheumatic diseases, improving physical function, aerobic capacity, and fatigue outcomes (4,5). However, exercise adherence remains a major challenge, often limited by pain, time constraints, and lack of motivation (6). Thus, innovative strategies that combine effectiveness with enjoyment are needed to promote long-term engagement in this vulnerable population.

Exergaming, which combines physical activity with interactive video games, enhances motivation and adherence while maintaining high energy expenditure (7). Non-immersive systems like WiiFit and Xbox Kinect have improved physical function and quality of life in children with JIA (8,9) but offer limited immersion. Advances in immersive virtual reality (IVR) now provide three-dimensional environments that boost enjoyment, energy use, and motor learning while reducing perceived exertion (10–12).

Fit-XR, a novel IVR exergaming platform available on the Oculus system, provides structured, multicomponent workouts (e.g., boxing, HIIT, dance) tailored to individual fitness levels. Previous studies have shown its feasibility, safety, and effectiveness in improving performance and enjoyment in healthy adults (13), supporting exercise in Parkinson's disease (14), and delivering high-intensity interval training in young adults (15). Similarly, early trials indicate that IVR exergames can enhance motor learning, energy expenditure, and motivation in neurological and musculoskeletal conditions (12). However, no study has yet examined Fit-XR in adolescents with JIA, where exercise adherence is often hindered by pain, fatigue, and low motivation.

This study aimed to compare the effects of two personalized, progressively adapted exercise interventions, a physiotherapist supervised personalized home-based program (HomeEX) and an immersive virtual reality based exergaming program (JiaFit-XR), on physical fitness, functional capacity, and physical activity in adolescents with JIA, and to determine whether the exergaming approach provides additional benefits beyond the physiotherapist supervised personalized exercise program.

Methods

Ethics

The study was approved by the Istanbul University-Cerrahpaşa Clinical Research Ethics Committee (No: 1795570, 06/06/2023) and conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants and guardians. The trial was prospectively registered at ClinicalTrials.gov (NCT06176846).

Study design and participants

This randomized, parallel-group controlled trial was conducted between December 2023 and January 2025 at three tertiary pediatric rheumatology centers. Adolescents aged 13–18 years with a confirmed JIA diagnosis (ILAR criteria) and adequate cognitive ability to perform exercises were included. Exclusion criteria were recent diagnosis (<1 month), surgery within the past year, active arthritis, or any medical condition limiting exercise tolerance or increasing cardiovascular risk. Additional exclusions included sensory impairments, anabolic medication use, non-compliance, or regular structured exercise within six months. Baseline demographic and clinical characteristics, including the number of previously affected joints and JIA subtype, were recorded. Accordingly, joint involvement reflects past rather than current active disease, as patients with active arthritis were excluded. Fifty eligible participants were randomized (1:1) to a personalized home-based program (HomeEX) or an immersive VR exergaming program (JiaFit-XR). Dropout rates were 36% (9/25) in HomeEX and 28% (7/25) in JiaFit-XR. Supplementary Figure S1 presents the CONSORT flow diagram. Randomization was computer-generated, and analyses followed the intention-to-treat principle. The HomeEX program was delivered by one physiotherapist, and the JiaFit-XR sessions were supervised by two. All assessments were performed by independent, blinded physiotherapists not involved in the interventions.

Interventions

Home-based exercise program

Participants in the HomeEX group followed a personalized, multicomponent program targeting balance, strength, agility, and endurance. Exercises were selected from a digital archive (~300 exercises) and compiled into individualized PDF booklets with photos, shared electronically with families. Each 25–30 min session included 8–10 exercises performed ≥ 10 repetitions, progressing in difficulty and frequency (≥ 2 /week). Typical exercises included squats, bridging, resistance-band movements, balance-board, and ball-based tasks (Supplementary Data S1). Participants in the HomeEX group performed the exercises independently between scheduled physiotherapist follow-ups, with parental support as needed. All were demonstrated at baseline, and adherence was monitored via exercise logs reviewed at weeks 1 and 4. Participants received a standardized equipment set (balance board, small ball, three resistance bands, and a stick with a band) used throughout the program.

Exergaming Program

JiaFit-XR exergaming intervention was delivered using the Oculus Quest 3 headset and the FitXR platform, which offers structured fitness modules such as *Boxing*, *HIIT*, *Combat*, *Sculpt*, and *Dance*. A progressive, multicomponent protocol targeting balance, strength, agility, and

1 endurance was designed, with games selected and adapted to participants' physical fitness
2 levels. Each session lasted 25–30 minutes, including a 4-minute warm-up and 3-minute cool-
3 down, and was performed twice weekly for eight weeks under physiotherapist supervision in
4 the clinic. Progression was achieved by gradually increasing the difficulty, duration, and variety
5 of games. During weeks 1–2, participants played *Boxing* at the beginner level. In weeks 3–4,
6 *Boxing*, *HIIT*, and *Sculpt* were introduced at the beginner level. In weeks 5–6, *Boxing* and
7 *Dance* were advanced to the intermediate level, and in weeks 7–8, participants engaged in
8 *Boxing*, *HIIT*, and *Dance* at the intermediate level. This staged progression ensured both
9 training variety and incremental challenge. Adherence was supported by physiotherapist
10 supervision, during which two physiotherapists provided feedback on technique, ensured safe
11 execution, and monitored participant engagement throughout the sessions. Game progression
12 logs were also reviewed weekly to verify compliance with the prescribed protocol. A detailed
13 week-by-week progression plan is provided in Supplementary Table S1.

14 Outcome Measurements

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17 The primary outcome was functional capacity, evaluated through standardized field tests. The
18 Six-Minute Walk Test was performed according to ATS guidelines to measure the distance
19 covered in six minutes, with cardiovascular parameters and fatigue ratings recorded before and
20 after the test (16). Lower-extremity strength and endurance were assessed using sit-to-stand
21 protocols: the One-Minute Sit-to-Stand Test (1MSTST), which also included a 30-second split
22 to capture early performance and fatigue trajectory, and a separate 30-Second Sit-to-Stand Test
23 (30STST) focusing on short-burst functional strength (17). In addition, step performance was
24 examined using a 10-step climbing and descending protocol; the Step Down Test (SDT) and
25 Step Up Test (SUT) recorded ascending and descending times to provide further indicators of
26 mobility and agility (18).

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29 Secondary outcomes encompassed broader aspects of fitness and activity. The FitnessGram
30 Test Battery was used to evaluate aerobic capacity, muscular strength, endurance, and
31 flexibility through the Progressive Aerobic Cardiovascular Endurance Run (PACER), Curl-up
32 Test (CT), Trunk Lift Test (TLT), Push-up Test (PT), and Back-Saver Sit-and-Reach Test
33 (BSSRT) (19). Lower extremity muscle strength was assessed using the K-Force handheld
34 dynamometer by measuring the maximal isometric strength of the quadriceps and hamstring
35 muscles at 30° and 60° of knee flexion, including endurance and inter-limb symmetry
36 parameters. The K-Grip for grip strength and fatigue indices; and the K-Myo for surface EMG
37 analysis of forearm activation (20). Upper extremity strength, primarily involving the shoulder
38 girdle, was assessed using the I-Y-T Athletic Shoulder test at 180°, 135°, and 90° abduction
39 angles. Maximal isometric force was measured in the prone position using a Kinvent K-Force
40 Plate (21).

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43 Daily physical activity levels were monitored through smartwatch-based step counts, with
44 participants submitting weekly summaries from their devices. Perceived exertion after training
45 sessions was documented using the Borg scale (22). In the JiaFitXR group, in game
46 performance metrics including total FITXR scores and calories expended were recorded after
47 each training session.

48 Statistical Analysis

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51 All data were analyzed using IBM SPSS Statistics version 29.0 (IBM Corp., Armonk, NY,
52 USA). The Shapiro–Wilk test was used to assess the normality of data distribution. A two-tailed
53 p-value <0.05 was considered statistically significant. Since the majority of variables followed
54 a normal distribution, parametric tests were applied. For participants who missed the final
55 assessment and had missing values across all outcome measures, the Last Observation Carried
56 Forward (LOCF) method was used to estimate the missing data. Descriptive statistics were
57 expressed as mean ± standard deviation (SD). For within-group comparisons, the Paired
58 Samples t-test was employed, while between-group comparisons were conducted using the
59 Independent Samples t-test for normally distributed variables. Changes in weekly step counts,
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in-game scores, calories expended, and Borg perceived exertion ratings were analyzed over time using repeated-measures ANOVA to evaluate progression trends across the 8-week intervention.

Power Analysis

A post hoc power analysis was conducted to determine the detectable difference between the two independent groups using G*Power 3.1 software. The analysis was based on the 1-Minute Sit-to-Stand Test (1MSTST), the study's primary outcome. Calculations assumed an effect size (Cohen's d) = 0.6883, significance level (α) = 0.05, and an initial sample size of 25 participants per group. Due to participant attrition ($n=9$; 36% in the HomeEX group and $n=7$; 28% in the JiaFitXR group), some missing data were present. To minimize bias and preserve statistical power, an Intent-to-Treat (ITT) approach was applied, including all participants originally randomized in the analysis. Following this adjustment, the observed statistical power was calculated as $(1-\beta) = 0.664$ (66.4%), indicating a moderate power level. Despite dropouts, this sample size remained adequate to detect meaningful between-group differences.

Results

The comparison between the groups showed similar demographic characteristics in terms of age, sex, height, weight, and BMI ($p>0.05$) (Table 1). In both groups, only one participant was left-handed, while all others were right-handed.

In the pre-treatment assessments, functional capacity, FitnessGram Test results, lower extremity muscle strength, grip strength, and muscle activation were similar between the groups, whereas the JiaFit-XR group showed significantly higher SUT and SDT scores compared to the HomeEX group ($p<0.05$). Post-intervention analyses revealed significant improvements in the 6MWT, SDT, SUT, and TLT in the JiaFit-XR group ($p<0.05$), while a significant increase in BSSRT R was observed only in the HomeEX group ($p<0.05$). Between-group comparisons showed that improvements in 1MSTST, SDT, and SUT were significantly greater in the JiaFit-XR group, while BSSRT R improvements were greater in the HomeEX group ($p<0.05$) (Table 2).

In terms of upper extremity strength, the HomeEX Group showed significant improvements in push-up performance, Athletic Shoulder I test (left), and Y and T tests (bilateral) along with corresponding average loads ($p<0.05$). Conversely, the JiaFit-XR Group demonstrated significant enhancements in push-up speed, push-up left maximum weight, Athletic Shoulder Y and T (left), T test left average weight, and T test left maximum reach ($p<0.05$). Between-group comparisons of upper extremity strength showed no significant differences ($p>0.05$). For lower extremity muscle strength, the HomeEX Group exhibited significant improvement only in left 30° hamstring strength ($p<0.05$), whereas the JiaFit-XR Group demonstrated bilateral gains in 30° hamstring strength ($p<0.05$). For lower extremity muscle strength, the JiaFit-XR Group achieved greater improvements in right and left 30° hamstring strength, as well as in average maximum RMS right and average RMS bilateral ($p<0.05$) (Table 3).

For upper-extremity performance on the AST, the HomeEX group showed significant within-group improvements at 180°, 135°, and 90° positions ($p<0.05$), whereas the JiaFit-XR group exhibited no meaningful pre-post change in AST peak or mean force. Between-group analyses of change favored HomeEX for several AST outcomes. In contrast, for lower-extremity muscle strength, the HomeEX group demonstrated a significant gain only in 30° hamstring strength on the left ($p<0.05$), while the JiaFit-XR group achieved bilateral improvements in 30° hamstring strength and greater increases in 30° hamstring strength overall, as well as in average maximum RMS (right) and average RMS (bilateral) (all $p<0.05$) (Table 3).

Regarding hand grip strength and muscle activation, the HomeEX Group demonstrated significant improvements in peak force right and average force bilaterally ($p<0.05$), while the

JiaFit-XR Group showed significant gains in right-hand strength percentage and fatigue resistance ($p < 0.05$). Additionally, the JiaFit-XR Group exhibited significant increases in average minimum RMS (bilateral), average maximum RMS right, and average RMS bilateral values ($p < 0.05$). In terms of grip strength parameters, peak and average force left improved more in the HomeEX Group, while average minimum RMS bilateral, average maximum RMS right, and average RMS right favored the JiaFit-XR Group ($p < 0.05$) (Table 4).

The analysis of weekly step counts over the 8-week period revealed no statistically significant differences between the HomeEX and JiaFit-XR Groups ($p > 0.05$). Both groups exhibited fluctuations in step counts during the study period; however, these variations were not statistically meaningful (Figure 1). The average weekly step count increased by 32.4% in the HomeEX Group from Week 1 to Week 2, followed by a slight decline (-2.1%) in Week 3. The JiaFit-XR Group demonstrated a more stable trend, with moderate week-to-week fluctuations. The largest positive change in the HomeEX Group was observed in Week 5 (+31.1%), whereas the JiaFit-XR Group exhibited its highest increase in Week 6 (+15.2%) and largest decrease in Week 3 (-7.8%). Repeated-measures ANOVA confirmed that weekly trends did not differ significantly between groups over time ($p > 0.05$), indicating that both groups followed a similar trajectory in physical activity levels. Tukey's post-hoc analysis further demonstrated that no single week differed significantly from others, suggesting no systematic upward or downward trend in either group.

The changes in 2-week averaged game scores, calories burned, and Borg fatigue levels throughout the 8-week intervention are summarized in Figure 2. Individual variations in game scores are presented in Figure 2a, and the 2-week averaged progression from repeated-measures analysis is shown in Figure 2b. Changes in calorie expenditure by participant are displayed in Figure 2c, with corresponding 2-week averaged trends shown in Figure 2d. Individual variations in Borg fatigue scores are illustrated in Figure 2e, and repeated-measures outcomes are presented in Figure 2f.

Repeated-measures analysis indicated a significant increase in mean game scores over time ($p < 0.05$), rising from approximately 600 in Weeks 1–2 to around 1700 in Weeks 7–8. Similarly, average calories burned increased significantly from ~75 kcal in Weeks 1–2 to ~160 kcal in Weeks 7–8 ($p < 0.05$). In contrast, Borg perceived exertion scores remained stable across the intervention (estimated marginal means 10.5–11.5; $p > 0.05$).

Discussion

In the comparison of two personalized exercise interventions for adolescents with JIA, both programs produced significant improvements in physical fitness, functional capacity, and activity levels. The JiaFitXR program led to greater gains in lower extremity muscle strength, endurance, and neuromuscular activation, whereas the HomeEX Program was more effective in improving upper extremity strength and flexibility. The superior outcomes observed in the JiaFitXR group highlight the potential of immersive exergaming to enhance engagement, reduce fatigue, and support motor learning in adolescents with JIA. This aligns with the growing body of musculoskeletal rehabilitation research emphasizing the integration of innovative, technology-driven methodologies to improve clinical outcomes (23).

Exergames have demonstrated benefits for both physical and psychological health across diverse age groups, including children, adolescents, and older adults (24–26). Previous studies utilizing non-immersive platforms such as Xbox Kinect™ have shown positive effects on physical function, grip strength, and quality of life among individuals with JIA (8,9). However, the therapeutic potential of IVR exergaming remains less explored. The IVR FitXR pilot study conducted among healthy university students demonstrated potential efficacy in reducing depression levels; however, no statistically significant effects were observed on anxiety or perceived stress levels (27). With the advent of affordable head-mounted displays, IVR exergaming has emerged as a promising tool that enhances motivation, adherence, and

1 enjoyment compared with traditional exercise. Evidence supports its safety and feasibility in
2 neurological and musculoskeletal populations, including cerebral palsy, multiple sclerosis,
3 Parkinson's disease, and older adults, and reports superior outcomes compared to conventional
4 resistance training in young adults (12,14,28,29). The present study extends this evidence by
5 demonstrating, for the first time, the feasibility and positive impact of an IVR exergaming
6 program on functional capacity and physical fitness in adolescents with JIA.

7 The 30STST is a valid, practical tool for assessing functional capacity in JIA, offering quick
8 and reproducible evaluation in clinics. Our previous work confirmed its feasibility and
9 sensitivity in this group (30). Consistent with prior research, structured exercise interventions
10 improve functional outcomes (31,32). Recent evidence highlights the benefits of personalized,
11 need-based programs for motivation and adherence (33–36). Similarly, Tarakci et al. reported
12 that a 12-week individualized program improved function and quality of life in JIA (37). Our
13 HomeEX program, designed with progressive and supervised sessions, produced gains in
14 30STST, push-up, and flexibility. The JiaFitXR group also showed marked improvements in
15 6MWT, stair-climbing, sit-to-stand, and ladder tests, indicating that dynamic, lower-limb-
16 focused VR activities can further enhance functional capacity.

17 Both interventions improved physical fitness, albeit with different emphases. The HomeEX
18 program primarily enhanced upper-body strength and flexibility, whereas the JiaFitXR program
19 elicited greater improvements in trunk lift performance, likely due to its dynamic, core-
20 engaging routines such as Boxing, HIIT, and Dance. Prior studies confirm that individualized
21 home exercise programs effectively improve physical fitness in children with chronic diseases,
22 while exergaming interventions have been shown to enhance strength, endurance, balance, and
23 quality of life (8,9,24–26,38). Although most prior studies examined non-immersive
24 exergames, recent evidence suggests that IVR-based modalities can yield superior adherence
25 and motivation (27). Our findings therefore provide novel evidence supporting the safety,
26 feasibility, and efficacy of IVR exergaming in improving physical fitness among adolescents
27 with JIA.

28 Both programs improved muscle strength through different mechanisms. For the lower limbs,
29 both groups showed gains in 30° hamstring strength, with greater improvements in the JiaFitXR
30 group. As JIA often affects lower limb strength and range of motion, strengthening knee
31 muscles is crucial for torque, stability, and function (1,18,39). Hamstring strength and fatigue
32 resistance are closely linked to balance and proprioception (40–42); thus, the dynamic, squat-
33 based exercises in FitXR (Boxing, HIIT, Dance) likely contributed to these gains. In contrast,
34 only the HomeEX group showed significant improvements in upper-limb endurance and
35 postural control, reflected in AST I–Y–T and push-up tests. While JiaFitXR did not increase
36 upper-limb strength, participants displayed better coordination and engagement, likely due to
37 its fast-paced, interactive format. Overall, home-based training enhanced upper-limb endurance
38 and control, whereas IVR exergaming offered motivational and neuromotor benefits
39 complementing JIA rehabilitation. Similarly, the absence of established normative data for AST
40 I–Y–T performance limits comparison with healthy reference populations.

1 Hand involvement is prevalent in JIA, with up to 80% of patients experiencing bilateral wrist
2 and finger involvement leading to impaired grip strength (43). Previous studies in different age
3 groups have reported inconsistent findings regarding grip strength outcomes. While Sandstedt
4 et al. reported no significant grip improvements after a 12-week strengthening program in adults
5 with JIA (39), Arman et al. demonstrated significant gains using Kinect-based exergaming in
6 pediatric populations (8). Similarly, Rashed et al. highlighted the clinical relevance of grip
7 strength in children and adolescents with JIA, showing its association with disease activity and
8 functional outcomes (43). Consistent with these findings, our study demonstrated significant
9 increases in grip strength in both groups after eight weeks. In the HomeEX group, gains were
10 more generalized (right-hand peak force and bilateral average force), while the JiaFitXR group
11 demonstrated right-hand-dominant improvements in fatigue resistance and neuromuscular
12 activation (RMS measures). The lack of change in the left hand likely reflects participants'
13 right-hand dominance. Taken together, these findings suggest that exercise-based
14 interventions—whether conventional or technology-supported—may be more effective in
15 improving grip strength in pediatric and adolescent JIA populations compared to adults. These
16 findings emphasize that both interventions can enhance grip function—critical for improving
17 daily living activities in JIA. However, the absence of established normative data for the
18 specific dynamometer and EMG-derived measures limits direct comparison with healthy
19 reference values.
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22 Over the 8-week intervention, both groups demonstrated increased weekly step counts, with no
23 statistically significant between-group differences. Although the JiaFitXR group exhibited a
24 more stable weekly pattern, both interventions promoted comparable levels of physical activity.
25 Given that step count is a widely used proxy for overall physical activity, and that higher levels
26 of physical activity are associated with improved physical fitness and overall health in children
27 and adolescents (44), these outcomes may be clinically relevant for individuals with JIA.
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30 Participants showed progressive gains in game performance and energy expenditure, indicating
31 improved physical capacity and endurance. Notably, perceived exertion (Borg RPE) remained
32 stable, suggesting physiological adaptation without increased fatigue, consistent with previous
33 findings that FitXR enhances performance while maintaining tolerable effort (14). The
34 immersive, gamified nature of IVR likely reduced fatigue perception and supported motivation
35 (45,46), a key advantage for fatigue management in JIA rehabilitation. Adherence is a well-
36 documented challenge in pediatric JIA rehabilitation, with rates ranging from 29% to 99%
37 depending on factors such as pain, enjoyment, parental involvement, and logistical barriers (6).
38 In this study, the overall attrition rate was 32% (16/50), slightly higher in the HomeEX group
39 (36%) than in the IVR group (28%). The most common barriers included school workload,
40 transportation difficulties, and the need for parental supervision. Importantly, adherence and
41 engagement were higher in the IVR group, likely due to the structured, physiotherapist-
42 supervised sessions and the gamified format. These factors may mitigate typical barriers to
43 adherence in JIA, supporting the feasibility and motivational potential of IVR-based
44 rehabilitation. This level of attrition is consistent with previous pediatric exercise studies.
45 Although it may introduce bias, the use of intention-to-treat analysis with LOCF imputation
46 likely mitigated its impact on the findings.
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51 Strengths of this study include its randomized controlled design, use of objective functional
52 measures, and integration of an innovative IVR platform in pediatric rheumatology. However,
53 several limitations should be acknowledged. Limitations include the modest sample size, short
54 8-week duration, reliance on smartwatch-based activity tracking, and lack of adverse event
55 assessment, warranting further long-term and comprehensive studies. The absence of patient-
56 reported outcomes, including quality of life and satisfaction measures, is another limitation and
57 should be addressed in future research. In addition, although both interventions were delivered
58 under physiotherapist supervision to ensure safety, adherence, and correct technique, this
59 requirement may limit scalability in broader healthcare settings. Future implementations may
60 benefit from hybrid models integrating remote monitoring, digital feedback systems, or

partially supervised protocols to enhance accessibility while preserving individualized care. Furthermore, the exclusion of participants with active arthritis was implemented to ensure safety and prevent potential exacerbation of symptoms during exercise; however, this may limit the generalizability of the findings to the broader JIA population. Future studies should investigate the safety and effectiveness of tailored exercise interventions in patients with active disease. While peer-based physical activity is important for participation, individualized. While peer-based physical activity is essential for participation, individualized physiotherapist-guided programs may serve as a transitional approach by addressing disease-specific limitations and facilitating safe engagement in broader activities.

Conclusion

Both home-based and IVR exergaming programs improved functional capacity, fitness, and daily activity in adolescents with JIA. The IVR program showed greater gains in lower-limb endurance, neuromuscular activation, and engagement, while the home-based program improved flexibility and upper-limb strength. These results support integrating IVR into personalized rehabilitation and exploring its long-term role in pediatric rheumatology.

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Authors' Contributions

[NAA, NA, FC] designed the study and supervised the research. [NAA, NA, FC, BS, AA, AY, YA, ID] performed data collection and interventions. [NA, AA, AY] carried out the statistical analysis. [NAA, NA, FC, BS, AA, AY, YA, ID] drafted the first version of the manuscript. All authors contributed to data interpretation, critically reviewed the manuscript, and approved the final version. All authors meet the ICMJE criteria for authorship.

Disclosure of Interest

The authors have declared no competing interests.

Data Availability Statement

The data underlying this article will be shared on reasonable request to the corresponding author.

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1. Figure 1. Progression of Point Score, Calorie Score, and Borg Score Over Time

- A - Weekly development of Point Score (Week 1–8)
- B - Estimated marginal means from repeated-measures analysis for Point Score
- C - Weekly development of Calorie Score (Week 1–8)
- D - Estimated marginal means from repeated-measures analysis for Calorie Score
- E - Weekly development of Borg Score (Week 1–8)
- F - Estimated marginal means from repeated-measures analysis for Borg Score

1 **Alt Text: Six-panel figure comparing HomeEX and JiaFit-XR across eight weeks. Panels A, C,**
2 **and E show weekly trends in point score, calorie score, and Borg score, and Panels B, D, and F**
3 **show estimated marginal means for the same outcomes, summarizing changes in performance,**
4 **energy expenditure, and perceived exertion over time.**
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6 **2. Figure 2. Average Step Count and Weekly Change Over 8 Weeks**

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8 A – Comparison of step count trends between the home-based exercise and immersive virtual
9 reality exergaming groups across 8 weeks
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11 B – Weekly changes in step count by groups: Statistical evaluation of progression
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13 *HomeEX: home-based exercise program, JiaFit-XR: Immersive virtual reality exergaming program*
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15 **Alt Text: Two-panel figure comparing HomeEX and JiaFit-XR across eight weeks. Panel**
16 **A shows step-count trends over time, and Panel B shows the statistical pattern of weekly**
17 **change, summarizing progression in ambulatory activity in both groups.**
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Table 1. Comparison of demographic characteristics of the groups

	HomeEX (n=25) Mean (SD)	JiaFit-XR (n=25) Mean (SD)	χ^2/t	P
Gender (Female/Male)	17/8	17/8	0.00	1.000
Age (year)	13.71 (1.82)	14.28 (2.17)	-1.74	0.090
Height (cm)	160.79 (9.19)	159.48 (12.54)	-0.33	0.740
Weight (kg)	58.44 (15.21)	58.47 (15.97)	-0.38	0.705
BMI (kg/m ²)	23.06 (5.38)	22.40 (4.42)	-0.28	0.781
Involved Joint Count (n)	3.64 (2.59)	3 (2.08)	0.96	0.341
JIA subtype			0.08	0.765
Oligo JIA (n)	17 (%68)	16 (%64)		
Poli JIA (n)	8 (%32)	9 (%36)		

STD: Standard Deviation, n: Sample Size, BMI: Body Mass Index, JIA: Juvenile idiopathic arthritis,

HomeEX: home-based exercise program, JiaFit-XR: Immersive virtual reality exergaming program

p: Independent Samples t-test

Table 2. Pre- and post-treatment comparison of functional capacity and FitnessGram Test's results within the group

Test	Group	Pre Mean (SD)	Post Mean (SD)	t	p ¹	pre-post Δ Mean (SD)	t (Δ)	p ² (Δ)
30STST	HomeEX	13.53 (2.82)	15.00 (2.64)	-2.15	0.050	1.47 (2.64)	-0.65	0.516
	JiaFit-XR	15.59 (2.29)	18.00 (4.23)	-1.91	0.074	2.41 (5.20)		
1MSTST	HomeEX	28.33 (4.74)	30.75 (5.96)	-2.16	0.041	2.42 (5.46)	-2.42	0.019
	JiaFit-XR	28.20 (4.38)	34.88 (8.24)	-5.03	0.001	6.64 (6.67)		
6MWT	HomeEX	543.94 (86.77)	577.38 (91.33)	-1.86	0.082	33.44 (71.83)	0.12	0.905
	JiaFit-XR	551.94 (62.42)	582.65 (50.47)	-2.22	0.041	30.71 (56.86)		
SDT	HomeEX	6.30 (1.05)*	7.00 (1.56)	-1.35	0.209	0.70 (1.63)	2.27	0.040
	JiaFit-XR	6.67 (1.11)*	6.07 (1.16)	2.55	0.023	-0.60 (0.91)		
SUT	HomeEX	3.37 (0.74)*	3.75 (0.70)	-1.42	0.197	0.37 (0.74)	2.48	0.031
	JiaFit-XR	3.64 (0.63)*	3.28 (0.61)	2.68	0.019	-0.35 (0.49)		
CT	HomeEX	13.69 (9.77)	15.69 (17.74)	-0.54	0.592	2.00 (14.61)	0.29	0.977
	JiaFit-XR	24.47 (23.47)	26.35 (22.64)	-1.06	0.304	1.88 (7.31)		
PT	HomeEX	2.06 (3.19)	3.50 (3.68)	-2.27	0.038	1.46 (2.64)	-0.65	0.516
	JiaFit-XR	3.71 (3.85)	4.47 (4.09)	-1.06	0.304	2.41 (5.19)		
PACER	HomeEX	7.20 (5.15)	9.27 (4.71)	-1.88	0.081	2.07 (4.25)	0.44	0.664
	JiaFit-XR	9.06 (2.99)	10.53 (5.53)	-1.84	0.083	1.47 (3.28)		
TLT	HomeEX	23.62 (8.90)	25.56 (4.70)	-0.94	0.361	1.93 (8.23)	-0.92	0.371
	JiaFit-XR	23.82 (4.30)	27.76 (4.75)	-5.36	<0.001	3.94 (3.03)		
BSSRT R	HomeEX	11.68 (10.87)	15.81 (10.77)	-2.58	0.021	4.12 (6.38)	2.15	0.042
	JiaFit-XR	18.23 (5.30)	18.52 (5.58)	-0.37	0.714	0.29 (3.26)		
BSSRT L	HomeEX	13.56 (8.34)	15.43 (10.27)	-1.59	0.132	1.87 (4.70)	1.05	0.304
	JiaFit-XR	17.64 (4.94)	18.11 (5.51)	-0.73	0.470	0.47 (2.62)		

STD: Standard Deviation, 30STST: 30 Second Sit-to-stand Test, 1MSTST: 1 Minute Sit-to-stand Test, 6MWT: 6 Minute Walk Test, CT: Curl Up Test, PT: Push Up Test, TLT: Trunk Lift Test, BSSRT: Back Saver Sit and Reach Test, SDT: Step Up and Down Test, SUT: Step Up Test, R: Right, L: Left, HomeEX: home-based exercise program, JiaFit-XR: Immersive virtual reality exergaming program

p¹: Paired Samples *t*-test, **p²**: Independent Samples *t*-test

* Only the variables marked with an asterisk (*) showed a significant difference between groups at baseline (Pre), based on the independent samples *t*-test ($p < 0.05$)

Table 3. Pre- and post-treatment comparison of lower and upper extremity muscle strength results within the group

		Pre Mean (SD)	Post Mean (SD)	t	p	Pre-Post Δ Mean (SD)	t (Δ)	p (Δ)
60° Q Strength L	HomeEX	20.14 (9.06)	22.24 (8.77)	-0.86	0.396	4.44 (8.14)	-0.26	0.794
	JiaFit-XR	21.20 (12.38)	20.36 (10.85)	0.32	0.747	5.13 (10.21)		
60° Q Strength R	HomeEX	19.84 (10.04)	19.14 (11.35)	0.198	0.845	2.36 (11.57)	-1.77	0.084
	JiaFit-XR	19.79 (11.13)	22.93 (12.15)	-1.50	0.147	7.63 (9.06)		
60° Q R/L Asymmetry	HomeEX	17.09 (11.99)	24.57 (24.22)	-1.26	0.219	10.53 (31.43)	0.62	0.539
	JiaFit-XR	16.74 (15.35)	20.19 (12.30)	-0.90	0.376	5.92 (18.87)		
30° H Strength L	HomeEX	10.99 (4.35)*	15.41 (6.07)	-3.10	0.005	5.68 (5.90)	1.14	0.260
	JiaFit-XR	15.76 (8.35)*	22.45 (8.39)	-4.09	0.001	3.45 (7.73)		
30° H Strength R	HomeEX	10.58 (5.04)	13.14 (4.51)	-1.96	0.062	3.08 (5.20)	-2.92	0.006
	JiaFit-XR	14.63 (8.73)	22.14 (8.47)	-3.87	0.001	9.07 (8.75)		
30° H R/L Asymmetry	HomeEX	14.84 (11.42)	15.32 (9.08)	-0.14	0.890	-2.98 (18.34)	1.96	0.056
	JiaFit-XR	20.49 (13.46)	14.40 (12.03)	1.71	0.101	-14.21 (21.65)		
AST-180°, Strength L (kg)	HomeEX	4.85 (1.50)	5.44 (1.40)	-2.234	0.035	0.59 (1.32)	1.82	0.075
	JiaFit-XR	5.76 (2.67)	5.41 (1.97)	789	0.437	-0.35 (2.19)		
AST-135°, Strength L (kg)	HomeEX	4.09 (1.43)	4.52 (1.14)	-1.838	0.078	0.44 (1.19)	0.52	0.600
	JiaFit-XR	4.51 (1.88)	4.74 (2.02)	-694	0.494	0.23 (1.63)		
AST-90°, Strength L (kg)	HomeEX	3.59 (1.03)	4.24 (0.91)	-3.303	0.003	0.65 (0.99)	2.1	0.041
	JiaFit-XR	4.10 (1.66)	4.04 (1.20)	231	0.819	-0.06 (1.39)		
AST-180°, Strength R (kg)	HomeEX	5.41 (1.79)	5.86 (1.57)	-1.588	0.125	0.45 (1.42)	1.43	0.159
	JiaFit-XR	5.89 (2.73)	5.51 (2.31)	0.75	0.460	-0.38 (2.51)		
AST-135°, Strength R (kg)	HomeEX	4.18 (1.21)	5.13 (1.34)	-4.671	<0.001	0.95 (1.01)	3.00	0.004
	JiaFit-XR	5.13 (2.28)	4.78 (1.76)	916	0.368	-0.35 (1.91)		
AST-90°, Strength R (kg)	HomeEX	3.67 (1.10)	4.40 (1.26)	-3.77	<0.001	0.73 (0.97)	1.70	0.096
	JiaFit-XR	4.56 (1.89)	4.62 (1.73)	-0.17	0.866	0.06 (1.72)		
AST-180°, mean force L (kg)	HomeEX	3.82 (1.11)	4.43 (1.13)	-3.137	0.004	0.62 (0.98)	2.09	0.042
	JiaFit-XR	4.47 (2.09)	4.29 (1.58)	552	0.585	-0.18 (1.63)		
AST-135°, mean force L (kg)	HomeEX	3.22 (1.06)	3.63 (0.97)	-2.278	0.031	0.41 (0.90)	1.44	0.155
	JiaFit-XR	3.61 (1.51)	3.59 (1.30)	0.06	0.952	-0.01 (1.16)		
AST-90°, mean force L (kg)	HomeEX	2.83 (0.89)	3.34 (0.74)	-3.298	0.003	0.51 (0.77)	1.94	0.058
	JiaFit-XR	3.22 (1.31)	3.23 (0.95)	-66	0.947	0.01 (1.01)		
AST-180°, mean force R (kg)	HomeEX	4.10 (1.32)	4.45 (1.16)	-1.416	0.169	0.35 (1.24)	1.07	0.286
	JiaFit-XR	4.40 (2.06)	4.28 (1.73)	337	0.739	-0.12 (1.80)		
AST-135°, mean force R (kg)	HomeEX	3.26 (0.96)	4.07 (1.06)	-4.203	<0.001	0.81 (0.97)	3.04	0.004
	JiaFit-XR	4.03 (1.79)	3.75 (1.35)	936	0.358	-0.28 (1.52)		
AST-90°, mean force R (kg)	HomeEX	2.96 (0.88)	3.52 (0.96)	-3.882	<0.001	0.56 (0.72)	1.59	0.120
	JiaFit-XR	3.54 (1.52)	3.59 (1.30)	-152	0.880	0.04 (1.46)		

STD: Standard Deviation, L: Left, R: Right, Q: Quadriceps, H: Hamstring, AST: Athletic Shoulder Test, HomeEX: home-based exercise program, JiaFit-XR: Immersive virtual reality exergaming program

p^1 : Paired Samples *t*-test, p^2 : Independent Samples *t*-test

* Only the variables marked with an asterisk (*) showed a significant difference between groups at baseline (Pre), based on the independent samples *t*-test ($p < 0.05$)

Table 4. Pre- and post-treatment comparison of grip strength and muscle activation results within the group

		Pre Mean (SD)	Post Mean (SD)	t	p	Pre-Post Δ Mean (SD)	t (Δ)	p (Δ)
Peak Force L	HomeEX	14.52 (4.29)	17.37 (3.64)	-3.54	0.002	3.62 (3.70)	4.15	0.001
	JiaFit-XR	17.82 (7.52)	16.31 (5.99)	1.23	0.231	-0.17 (2.61)		
Peak Force R	HomeEX	15.77 (4.62)	18.05 (5.39)	-2.10	0.047	2.44 (5.11)	0.82	0.415
	JiaFit-XR	19.12 (8.16)	18.37 (5.20)	0.52	0.605	1.52 (1.87)		
Average Force L	HomeEX	11.52 (3.98)	14.07 (3.61)	-3.26	0.003	3.52 (3.88)	3.22	0.003
	JiaFit-XR	14.90 (6.58)	14.19 (5.57)	0.66	0.513	0.48 (2.55)		
Average Force R	HomeEX	12.12 (4.02)	14.73 (4.84)	-2.78	0.011	2.87 (4.48)	1.33	0.190
	JiaFit-XR	15.56 (6.89)	15.54 (4.70)	0.01	0.989	1.52 (2.12)		
Time to Max. L	HomeEX	2.23 (1.52)	2.16 (1.22)	0.14	0.886	-0.06 (2.11)	-0.48	0.630
	JiaFit-XR	1.92 (1.36)	2.12 (1.44)	-0.61	0.547	0.19 (1.60)		
Time to Max. R	HomeEX	2.38 (1.14)	2.90 (1.04)	-2.01	0.056	0.50 (1.23)	1.78	0.081
	JiaFit-XR	2.63 (1.30)	2.49 (0.81)	0.54	0.592	-0.14 (1.30)		
Fatigue L	HomeEX	-2.11 (3.84)	-1.43 (0.66)	-0.85	0.404	1.25 (4.89)	1.46	0.150
	JiaFit-XR	-1.15 (0.85)	-1.16 (1.25)	0.02	0.981	-0.22 (1.27)		
Fatigue R	HomeEX	-1.48 (1.16)	-2.10 (3.01)	0.95	0.348	-0.05 (3.27)	-0.62	0.542
	JiaFit-XR	-1.72 (0.98)	-1.23 (0.73)	-1.71	0.099	0.38 (1.33)		
Average Max. RMS L	HomeEX	7.05 (1.53)	7.33 (1.65)	-0.74	0.465	0.81 (2.53)	1.42	0.166
	JiaFit-XR	7.53 (2.24)	8.26 (1.51)	-1.54	0.137	-0.12 (1.37)		
Average Max. RMS R	HomeEX	6.91 (1.26)	7.38 (2.45)	-1.02	0.320	-0.45 (1.90)	-2.79	0.008
	JiaFit-XR	8.39 (2.67)	10.06 (2.00)	-2.43	0.023	1.06 (1.88)		
Average Min. RMS L	HomeEX	0.31 (0.33)	0.43 (0.44)	-0.95	0.348	-0.01 (0.41)	-2.88	0.006
	JiaFit-XR	0.28 (0.15)	0.73 (0.48)	-4.39	0.001	0.42 (0.55)		
Average Min. RMS R	HomeEX	0.37 (0.37)	0.35 (0.17)	-1.78	0.088	0.02 (0.23)	-3.53	0.001
	JiaFit-XR	0.33 (0.29)	0.79 (0.49)	-4.00	0.001	0.42 (0.51)		
Average RMS L	HomeEX	4.78 (1.02)	5.31 (1.29)	-1.78	0.088	0.61 (1.86)	1.13	0.269
	JiaFit-XR	5.64 (1.63)	6.39 (1.14)	-2.19	0.039	0.05 (1.09)		
Average RMS R	HomeEX	4.82 (1.02)	5.22 (1.48)	-1.36	0.186	-0.11 (1.35)	-3.68	0.001
	JiaFit-XR	5.93 (1.47)	7.56 (1.54)	-4.03	0.001	1.30 (1.34)		

STD: Standard Deviation, L: Left, R: Right, Min: Minimum, Max: Maximum, RMS: Root Mean Square, HomeEX: home-based exercise program, JiaFit-XR: Immersive virtual reality exergaming program

p^1 : Paired Samples *t*-test, p^2 : Independent Samples *t*-test

* Only the variables marked with an asterisk (*) showed a significant difference between groups at baseline (Pre), based on the independent samples *t*-test ($p < 0.05$)

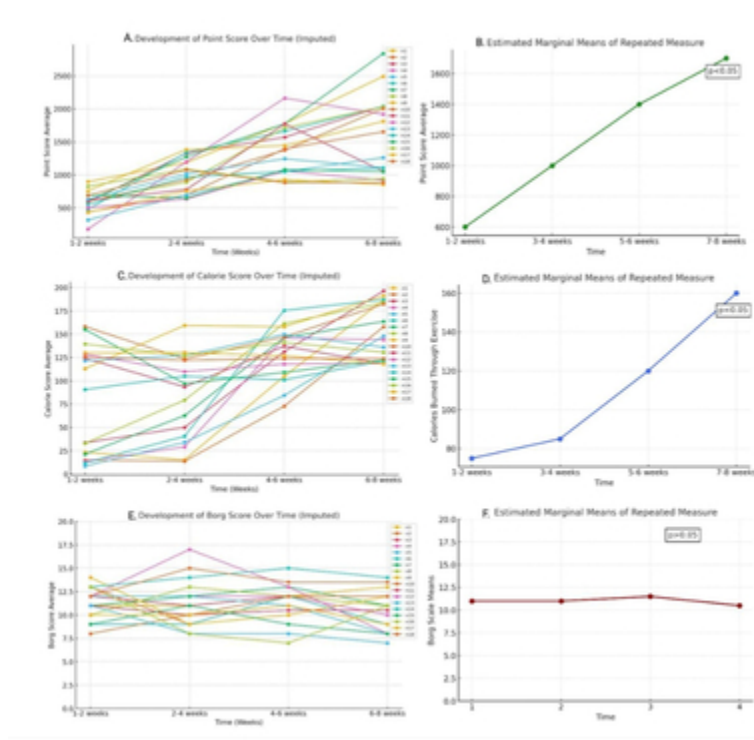


Fig 1

32x31mm (300 x 300 DPI)

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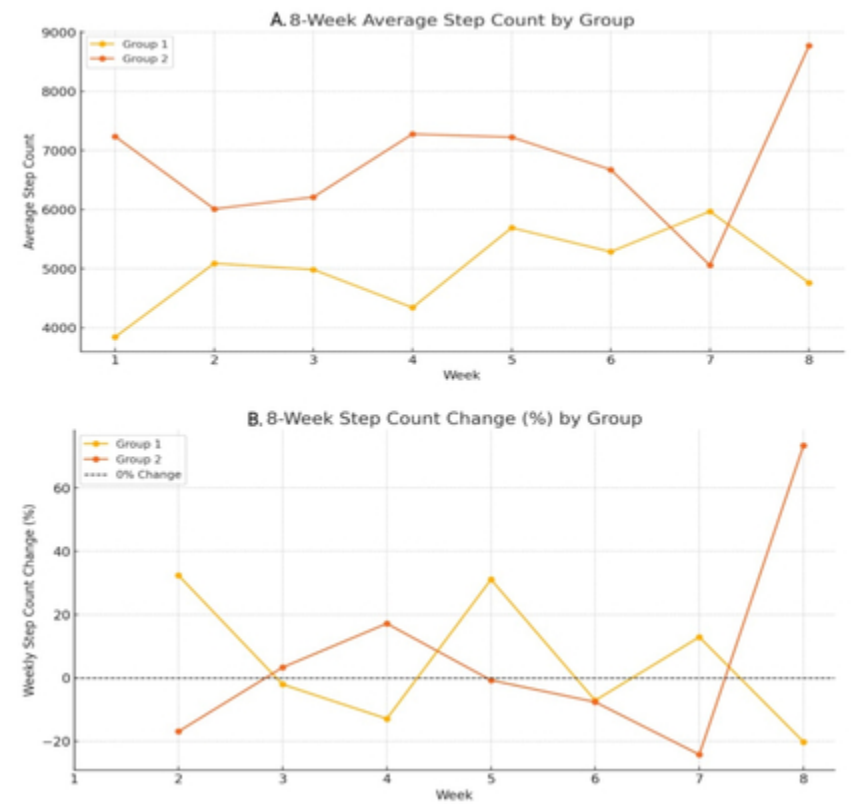


Fig 2

36x34mm (300 x 300 DPI)