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Research article

Exploring the effects of anti-gravity treadmill training in musculoskeletal disorders: A systematic review

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ABSTRACT

Musculoskeletal disorders (MSD) comprise a great variety of medical conditions, and the economic and sanitary burdens they cause are a major concern for the sanitary systems worldwide. Conventional rehabilitation is effective; however, with the rise of new technologies, it can be further improved. Anti-gravity treadmills are starting to enter the clinical rehabilitation practice of MSD due to their characteristics, which allow weight support while performing walking and running exercises. Thus, this systematic review aims to explore the effects and use of anti-gravity treadmills in MSD. A systematic search of literature was performed by collecting articles from PubMed, Scopus, and Web of Science on the use of anti-gravity treadmills in MSD management. The PEDro scale tool and the Joanna Briggs Institute checklist were used to assess the methodological quality of the included studies. Relevant data were collected in tables, and the primary outcomes were discussed narratively. Of the 185 articles screened, 11 were included in the qualitative synthesis. The findings of the selected articles encourage the use of anti-gravity treadmills in MSD rehabilitation to improve gait functionality, balance, pain relief rct, range of motion, and fracture healing. The protocols and outcomes evaluated showed high heterogeneity, and quantitative synthesis could not be performed. In conclusion, the anti-gravity treadmill proved feasible, safe, and well tolerated by individuals with different MSD, and greater improvements were seen in participants who performed anti-gravity exercises than in those who performed only conventional rehabilitation.

1. Introduction

Musculoskeletal disorders (MSD) are currently the second leading cause of non-fatal disabilities, affecting millions of people worldwide [1]. These disorders include a broad spectrum of conditions affecting bones, muscles, joints, tendons, and ligaments and can result from acute injuries, repetitive stress, age-related degeneration, and chronic inflammatory conditions. Future projections on the incidence of these disorders are indicating a progressive trend, and it is estimated that by 2050, the number of people with MSD will double from 494 million in 2020 to 1.06 billion [2]. The management and treatment of these conditions require targeted therapeutic interventions to promote pain relief, quality of life, well-being, and healing [3]. Physical activity is widely considered a key factor in the management [4] and prevention of MSD [5]. Regular physical exercise improves muscle strength and flexibility, reduces pain, and

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improves physical function [2,6]. Studies have shown that structured exercise programs can lead to significant improvements even in individuals with various MSD, such as osteoarthritis [7], fractures [8], and tendon injuries [9]. Given the significant benefits of physical activity, there is growing interest in incorporating innovative technologies to enhance rehabilitation outcomes. In this context, the introduction of new technologies, such as the anti-gravity treadmill (AGT), could offer new opportunities for prevention, treatment, and recovery. The AGT uses the positive pressure of compressed air within a closed and locked structure [10] that wraps around the lower half of the participant's body. An airtight inflatable wrap is installed in the treadmill, and the participant has to wear a special pair of shorts with a zip around the waist, which is then closed at the top [11]. With this instrument, a more sensitive adjustment of body weight support can be provided, considering that AGT can support up to 80 % of the body weight. AGT allows a controlled decrease in joint forces and has proven to be an effective tool in the rehabilitation of patients after lower-limb surgery [12]. Currently, AGT is increasingly used both in MSD and sports injury treatment to ameliorate time recovery for return to play, including in patients with running injuries [13], and in managing people with osteoarthritis [14], cerebral palsy [15], and pelvic stress fractures [16] with high safety standards. Furthermore, in patients undergoing total knee replacement, the force applied to the knees decreased during walking on an anti-gravity treadmill, in line with the reduction in load on the lower limbs [12]. Considering that individuals with MSD benefit from physical activities with low stress on the lower limbs, we investigated the role and possible effectiveness of AGT as a therapeutic exercise tool in this context. This study aimed to conduct an up-to-date review of the current literature, qualitatively analyze the effects of AGT in the treatment of MSD, and evaluate its potential efficacy in reducing symptoms, accelerating recovery time, and optimizing physical function in patients with different diseases.

2. Materials and methods

2.1. Search strategy

A systematic review of the literature was conducted on May 10, 2024, from the inception of databases, using PubMed, Web of Science, and Scopus. Articles investigating the use of anti-gravity treadmill in musculoskeletal disorders management were selected according to the following keywords: ("microgravity" OR "anti-gravity") AND ("osteoarthritis" OR "fracture" OR "musculoskeletal disorders") AND ("treatment" OR "exercise"). The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines were used [17]. The exclusion criteria were as follows: articles regarding healthy subjects, animals, in vitro studies, space-related studies, and case reports. Only original articles, including randomised controlled trials (RCTs), intervention design, observational and cross-actional studies, which met the following PICO criteria were included in the qualitative summary.

- Population: individuals affected by musculoskeletal disorders
- Intervention: administering of anti-gravity training
- Comparison: anti-gravity treadmill training compared to land or normal gravity training
- Outcome: effects on well-being, physical function, and autonomy.

2.2. Selection process

The articles were stored in EndNote 20 (EndNote 20 desktop version, Clarivate, Philadelphia, PA) [18] and duplicate articles were selected and automatically removed. Two independent investigators were separately involved in the screening and analysis processes. When a disagreement was present in the selection process, the principal investigator resolved it. The titles and abstracts of these articles were screened. Only original articles on humans were retrieved for selection, excluding case reports with only one individual investigated. Second, the full text of the selected articles was screened, with further exclusion for space-related studies, no use of an anti-gravity treadmill, or healthy subjects. The references of the selected studies for inclusion were screened to include other potentially relevant studies.

2.3. Data collection

The full texts of all selected articles were read to identify meaningful information. Relevant data extracted from the selected studies included the number of patients, sample classification, age, sex, range, anti-gravity treadmill protocol used, anti-gravity treadmill training results, outcome evaluated, and conclusions.

2.4. Risk of bias assessment

The PEDro scale tool [19] was used to assess the methodological quality and the risk of bias of the randomized clinical trials included in the review, and the Joanna Brig Institute checklist (JBI) for cohort studies was employed for the same purpose as the other articles included in the other studies. The PEDro scale, which consists of 11 items, assesses both the external and internal validity of the study. Each criterion that was met earned one point, with scores interpreted as follows: 9–10 points indicate excellent quality, 6–8 points indicate good quality, 4–5 points indicate fair quality; and less than 4 points, poor quality. The JBI checklist is a tool specifically developed for research synthesis and consists of 11 items; each question is defined as Yes, No, Unclear, or Not Applicable. Each study was evaluated for all domains, providing a single general score for all studies by two investigators who then discussed when disagreement was present.

3. Results

Of the 185 articles screened, 48 were screened by full text; instead, 22 articles were excluded due to their topic related to space, 16 were excluded because they did not use the anti-gravity treadmill, 2 were considered a healthy population, and 1 was a case study. The references of the 7 studies selected for inclusion were screened, and 4 other relevant studies were identified and included in the final qualitative synthesis, resulting in a total of 11 studies. The screening process, in the form of a flow diagram, is shown in Fig. 1.

All included articles administered physical activity with an anti-gravity treadmill, and seven of them had a control group. The study designs of the included articles were distributed as follows: 6 RCTs [20–25], 1 cross-sectional [14], 1 randomized cross-over [26], 1 pilot study [27] , and 2 observational [28,29]. The study included 386 participants, of whom 246 were allocated to the intervention group and 140 in the control group. The participants' musculoskeletal conditions in both groups were: 16 Achilles tendon repairs [27], 14 anterior cruciate ligament reconstructions, and meniscectomy [29], 103 total knee arthroplasty [20,21,26], 20 osteoarthritis [14], 34 femoral fracture [21], 38 hip fractures [22], 136 ankle fractures [23–25], and 25 tibial plateau fracture [23,24]; Fig. 2 give a representation of the study population. Although a sufficient number of studies were RCTs, it was not possible to perform a quantitative synthesis due to high heterogeneity in the outcome evaluated. The characteristics of the included studies are shown in Table 1.

3.1. Risk of bias assessment

The PEDro scale and JBI tool were used to assess the quality of the included studies according to their study design. When evaluated using the PEDro scale, four studies achieved a score of 7 (good quality), one study of 8 (good quality), and one study of 9 (excellent quality). The scores of the studies assessed using the JBI tool were lower, with three studies obtaining 6, one study 4, and one study 5, indicating a generally lower quality. The assessment of quality is reported in Table 2, and the used scales are reported in supplementary materials.

Regarding the risk of bias for the studies evaluated using the PEDro scale, the items not considered valid were mainly those assessing the blinding of the participants and therapists to the intervention. This was because of the nature of the treatment itself,

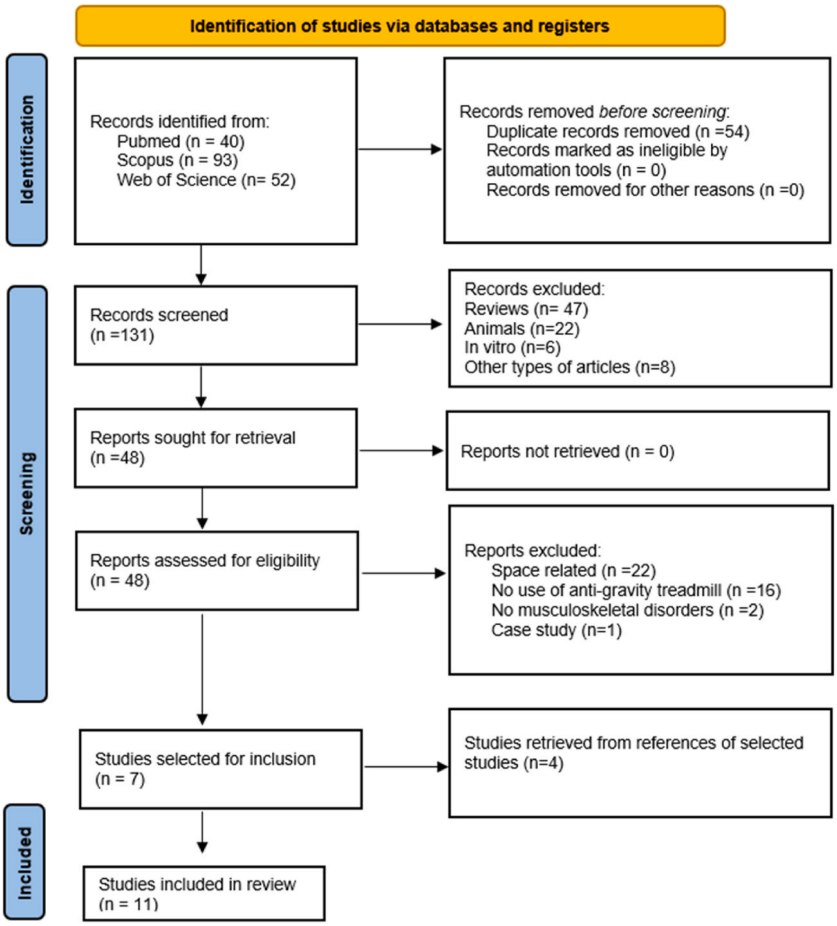

Fig. 1. PRISMA flow diagram for new systematic reviews that included searches of databases and registers.

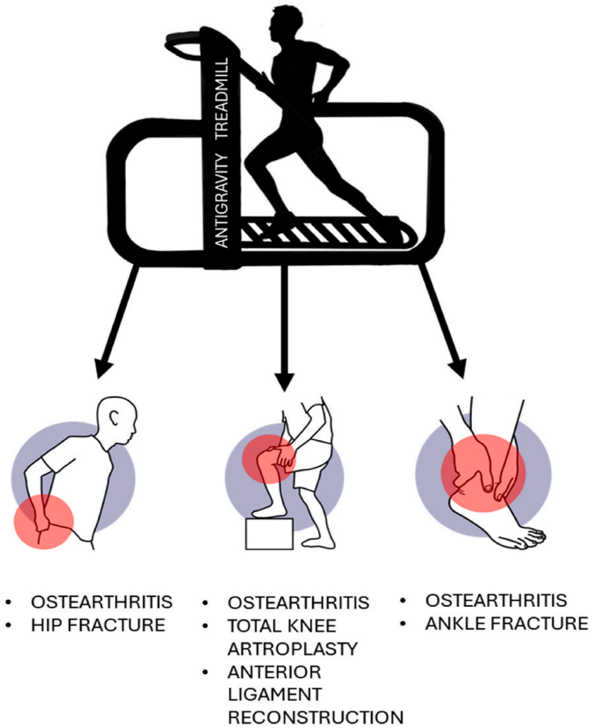

Fig. 2. MSD in which anti-gravity treadmill was employed.

which involved physical activity on a specific instrument. For studies evaluated using the JBI tool, the main issue was related to the absence of a control group and follow-up, considering the authors' choice of employing a cross-sectional or observational study design.

3.2. *Anti-gravity treadmill protocols*

Of the 11 included studies, considering the differences in study design, only two authors employed the same protocols [23,24]; all the other studies presented heterogeneity in the protocol used, regardless of whether the study designs were different. The range of weight reduction administered to the participants who performed anti-gravity treadmill walking training was between 20 % and 85 %. A fixed weight reduction of 20 kg was used in 2 studies. In one study, the duration of training was determined by the capacity of participants without a predetermined time. The other RCTs had a training intervention duration of 10–20 min. The other studies included other designs that employed different durations of training to evaluate the effects of the anti-gravity exercise, ranging from 8 to 32 min. In terms of velocity, there were consistent differences between the studies, and the range varied from 0.8 mph to 2.3 at the start of the intervention. The most common practice was to keep the speed self-paced, without manifesting discomfort, from the participants and, in RCT studies, to increase it throughout the sessions alongside an adjustment of the treadmill's slope.

3.3. *Effects on evaluated outcomes*

The effects of anti-gravity training on different outcomes were considered in the included studies, varying from diastolic and systolic pressure, oxygen uptake, functionality, autonomy in activities of daily living, muscle activity, return to activity time, ROM, isokinetic strength, rate of perceived exertion, pain, and fracture healing. Intervention with AGT was considered safe and feasible in all studies. In patients with tibial plateau and ankle fractures, positive clinically relevant changes in the knee injury and osteoarthritis outcome score subscale symptoms and quality of life occurred [23,24]; in addition, the ROM and dynamic gait index showed improvement over time, favouring the intervention in comparison with the normal gravity exercise control [24]. Moreover, it was found that after 8 weeks of AGT treatment, an enhancement in the quality score of bone scab, bone density, ankle-hindfoot scores, VAS pain score, and ankle ROM occurred compared to the control [25]. However, after eight weeks, no differences in joint swelling were found between the control and intervention groups [25]. Regarding the effects on people with hip fractures, it appears that adding 20 min of AGT intervention for 10 consecutive working days to a 2 weeks rehabilitation protocol improved Koval, FAC, Berg Scale, and EQ-5D scores at 6-months significantly more than conventional rehabilitation alone [22]. Moreover, in patients with femoral fractures who underwent 20 min of AGT for 4 weeks, the enhancement in isokinetic muscle strength of the hip extensor and gluteus muscle activities was higher than that in the conventional rehabilitation group [21]. In patients who underwent total knee arthroplasty, AGT walking with 40 % body weight support allowed them to walk at faster speeds and tolerate greater incline compared to no weight reduction [26]; moreover, a lower heart rate, systolic blood pressure, and oxygen consumption was observed, and it was highlighted

Table 1
Characteristics of the included studies.

Author, year	Study design	Control group participants (Age in years)	Intervention group participants (Age in years)	Gender of Control group (F/M)	Gender of Intervention group (F/M)	Participants' condition	Outcome evaluated
Eastlack, 2005 [29]	Quasi-Experimental design	NA	14 (41)	N/A	5/9	Meniscectomy and ACL reconstruction	Gait, GRF, ROM, muscle activity
Saxena, 2011 [27]	Pilot study	8 (38 ± 16.2)	8 (42 ± 10.6)	3/5	4/4	Achilles tendon repair	Return to activity time
Webber, 2014 [26]	Randomized cross-over	NA	24 (64.6 ± 7.9)	N/A	12/12	UTKA	Systolic and diastolic blood pressures, oxygen consumption, Borg scale, NRS
Bugbee, 2016 [20]	RCT	15 (69.9 ± 7.8)	14 (66.5 ± 7.8)	9/6	7/7	TKA	KOOS, TUG, NRS
Kawae, 2017 [14]	Cross-sectional	NA	20 (62.8 ± 10.8)	NA	12/8	Lower limbs osteoarthritis	Borg scale, NRS, walking speed, oxygen uptake, calorie consumption
Kim, 2020 [21]	RCT	17 (51.82 ± 5.91)	17 (48.82 ± 5.96)	4/13	4/13	Femoral fracture	Isokinetic strength, muscle activity
Oh, 2020 [22]	RCT	19 (81.15 ± 4.9)	19 (76.94 ± 9.43)	13/6	13/6	Hip fracture	Koval walking ability score, FAC, Berg scale, MMSE, EQ-5D, Barthel index
Kim, 2020 [28]	observational	NA	25 UTKA (72.6 ± 4.9) 25 BTKA (71 ± 5.4)	N/A	43/7	TKA	TUG, 10MWT, cardiorespiratory responses, pain
Henkelmann, al 2021 [23]	RCT	20 AF (40 ± 13) 6 TPF (44 ± 9)	23 AF (43 ± 12) 7 TPF (42 ± 9)	15/12	16/16	Lower limbs fractures	KOOS, FAOS, muscle atrophy
Palke et al., 2022 [24]	RCT	22 AF 7 TPF (43 ± 11)	19 AF 5 TPF (41 ± 12)	15/12	16/16	Lower limbs fractures	KOOS, FAOS, muscle atrophy, ROM ankle and knee, dynamic gait index
Chen et al., 2024 [25]	RCT	26 (39.73 ± 12.57)	26 (40.73 ± 9.40)	16/10	14/12	Ankle fracture	Fracture healing, joint recovery, pain, mobility, swelling

N/A: not available; ACL: anterior cruciate ligament; GRF: ground reaction force; ROM: range of motion; RCT: randomized clinical trial; UTKA: unilateral total knee arthroplasty; KOS-ADL: Knee Outcome Survey Activities of Daily Living Scale; TUG: timed up go test; SCT: stair climb test; KOOS: knee injury and osteoarthritis outcome score; TKA: total knee arthroplasty; NRS: numeric pain rating scale; FAC: functional ambulatory category; MMSE: mini-mental state; EQ-5D: Euro Quality of Life Questionnaire Five Dimensional Classification; 10MWT: 10 m walking test; BTKA: bilateral knee arthroplasty; AF: ankle fracture; TPF: tibial plateau fracture; FAOS: foot ankle outcome score.

that the higher the body weight support, the lower the cardiovascular responses [28]. In addition, an RCT detected an improvement in Timed Up and Go (TUG) in the AGT training group at the end of physical therapy compared to land-based exercises, but no differences between groups were found for Knee injury and Osteoarthritis Outcome Score (KOOS) and Numeric pain Rating Scale (NRS) scores [20]. In individuals with Achilles tendon repair, an effect of a 2-week reduction in the return to activity was seen in those who performed rehabilitation with the addition of 10 min AGT per session compared to conventional rehabilitation [27]. Positive effects in reducing pain and ameliorating knee ROM of AGT were evidenced in the postoperative rehabilitation of anterior cruciate ligament reconstruction and meniscectomy [29]. Less pain was also detected in people with osteoarthritis, where the participants performing AGT walking were able to walk at a higher speed, enhancing calorie consumption in comparison with no body weight support walking participants [14].

4. Discussion

This review aimed to synthesize the data currently available in the literature regarding the effects of AGT training in people recovering from MSD. Based on the evidence from the included studies, it came to light that AGT exercises are feasible and safe and can be employed in the rehabilitation of different types of MSD. The main effects detected were reduced cardiovascular stress and pain in the areas affected by the disorders when performing exercise with AGT. AGT can improve gait functionality and ROM, especially in people recovering from lower limb fractures.

As reported by the GBD 2019 Fracture Collaborators in the Lancet Healthy Longevity [30], fractures are a globally relevant problem for public health systems, and finding new ways to manage affected individuals is necessary. AGT training has been reported to be safe and feasible by different authors [21–25]. The reduction of weight load possible with properly designed treadmills proved their usefulness in rehabilitation, allowing training early in the recovery process and improving posture and gait patterns. Analysing all the

Table 2
Quality assessment of randomized controlled trials with the Pedro scale and the Joanna Briggs Institute tool for cohort, quasi experimental design and cross-sectional studies.

Author	Assessment tool	1	2	3	4	5	6	7	8	9	10	11	Total score
Bugbee et al [20]	Pedro scale	✓	✓	X	✓	X	X	X	✓	✓	✓	✓	7
Kim et al [21]		✓	✓	✓	✓	X	X	X	✓	✓	✓	X	7
Oh et al [22]		✓	✓	✓	✓	✓	X	X	✓	✓	✓	✓	9
Henkelmann [23]		✓	✓	✓	✓	X	X	X	X	✓	✓	✓	7
Palke et al [24]		✓	✓	✓	✓	X	X	X	X	✓	✓	✓	7
Chen et al [25]		✓	✓	✓	✓	X	X	X	✓	✓	✓	✓	8
Saxena et al [27]	JBI for cohort studies	✓	?	X	X	X	✓	X	✓	✓	X	X	4
Webber [26]		n/a	n/a	✓	✓	✓	✓	✓	n/a	n/a	n/a	✓	6
Kim et al [28]		✓	✓	✓	X	X	✓	✓	n/a	n/a	n/a	✓	6
Eastlack [29]	JBI for quasi experimental design	✓	✓	✓	✓	✓	✓	✓	?	✓			8
Kawae [14]	JBI for cross sectional studies	✓	✓	✓	✓	X	X	✓	✓				6

study included in the qualitative synthesis, there were notable differences in the percentages of body weight support administered to the participants. This could be due to the condition of the patients, their age and levels of physical fitness. Moreover, another factor could be the decision of different authors on when starting the intervention, considering that starting early, during the initial recovery phase, may require a higher percentage of body weight support. The effects on the quality score of the bone scab and bone density of the ankle after AGT training [25] may be due to the enhancing effects of exercise training on bone health [31] and bone density, as reported in a previous study [32]. Palke et al. [24] and Henkelmann et al. [23] also studied the effects of AGT in a population with ankle fractures and found improvements in the dynamic gait index, knee ROM, pain, and quality of life. One potential contributing factor could be the early initiation of postoperative rehabilitation that could reduce the detrimental effects of physical inactivity, thus allowing physical activity to be started as soon as possible [33]. In line with the improvement in the ROM of the knee and pain, there were also the findings by Eastlack et al. [29] found that these two variables were positively influenced by AGT training in individuals who had undergone meniscectomy and anterior cruciate ligament reconstruction. AGT was also employed in the rehabilitation of femoral fractures with positive results in improving static and dynamic balance, and functionality of gait more than conventional rehabilitation alone [22]. The potential reason for the improvement in balance could lie in the enhancement in isokinetic muscle strength of the hip extensor and gluteus muscle activities, which is higher than that achieved with conventional rehabilitation [21]. In osteoarthritis patients [14], it was observed that AGT can help improve speed velocity and allow more calorie consumption. This could represent a beneficial secondary factor of osteoarthritis rehabilitation, taking into account the well-established association between obesity and osteoarthritis [34] and the importance of maintaining adequate weight in the elderly for health implications [35]. An enhancement in speed velocity using AGT was observed in patients who underwent total knee arthroplasty, where an augmented tolerance to treadmill incline was detected [26]. The timed up-go test also improved in this population of patients [20], indicating an increment in physical function [36] and a lower risk of falls [37]. Alongside this, the cardiovascular stress due to activity was lower in the AGT group [28], suggesting that it could be possible that people with total knee arthroplasty could benefit from AGT rehabilitation by increasing the volume of training. Training volume, properly adapted to an individual's needs, is directly correlated with benefits for longevity, especially for the elderly [38], and improvement in both cardiorespiratory fitness [39] and muscles [40]. Practitioners could use this information to adjust the body weight support based on the condition of the patients and the timing of the rehabilitation. Moreover, considering that higher body weight support elicited lower cardiovascular responses [28], it might be beneficial to use a high body weight support at the start of the rehabilitation, especially in population at risk of manifesting cardiovascular events. The effects of AGT rehabilitation were also investigated in post-surgery Achilles tendon repair, finding that the AGT group recovered more quickly than the conventional rehabilitation group [27]. However, due to the small sample size and low quality of the study, this finding should be interpreted with caution. Interestingly, the most common decision from authors that employed AGT was to use the self-paced velocity from the participants for the intervention. This could be explained by the fact that in some pathological cohort of patients, for example in people who suffered a stroke, it was found that there are no detectable clinically relevant kinetic and kinematic differences between self-paced and fixed velocity [41]. In addition, in healthy subjects, there are no significant differences in the energy expenditure, biomechanics, spatiotemporal and kinematics variables between self-paced and fixed walking speed [42]. Hence, it is possible that the authors of the examined papers decided to employ self-paced velocity to avoid any possible problem related to the imposition of a certain velocity to their participants. The main limitation of our study is that the studies included in this review had people with different musculoskeletal disorders; thus, the protocols employed by the authors of the study were different in terms of the percentage of weight support, speed, and number of weeks of treatment. Therefore, it was not possible to quantitatively synthesize the data due to high heterogeneity and, also, it was not possible to provide a mean for the percentage of weight reduction used in the studies. Another limitation was the impossibility of providing guidance about when higher or lower levels of weight support might be appropriate due to the lack of studies treating this topic. Lastly, some of the non-RCT studies were of low quality, so their results must be interpreted with caution.

5. Conclusion

The employment of AGT training for people with MSD can beneficially impact the rehabilitation process. Despite differences in protocols, microgravity training interventions consistently demonstrated safety, feasibility, and low dropout rates. Clinically relevant improvements were detected in ROM, gait functionality, and pain reduction in individuals with ankle, hip, and femoral fractures, total knee arthroplasty, Achilles tendon repair, and postoperative anterior cruciate ligament reconstruction. AGT seems to represent a valid option for MSD management to differentiate the treatment of classic conventional rehabilitation. However, more trials with comparable outcomes and training protocols are needed to allow quantitative synthesis of data to determine the efficacy of this methodology with conventional rehabilitation.

CRediT authorship contribution statement

Bruno Trovato: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martina Sortino:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Federico Roggio:** Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Giuseppe Musumeci:** Writing – review & editing, Writing – original draft, Resources, Project administration, Funding acquisition, Conceptualization.

Data and code availability

No data was used for the research described in the article.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e40605.

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