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ORIGINAL STUDY

The effect of anti-gravity training after meniscal or chondral injury in the knee. A systematic review

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Reduced impact loading or anti-gravity training has recently been introduced as a new tool in the rehabilitation of orthopaedic conditions that require restricted weight bearing. The purpose of this strategy is to speed up the functional rehabilitation while at the same time protect the healing structures from harmful effects associated with impact loading. Anti-gravity treadmills (AlterG ®) and harness suspension devices seem to be the two most promising techniques. It is however today unclear how effective these devices are.

The purpose of our study was therefore to perform a systematic literature review on the actual technology available and its effect on impact load reduction, as well as its effectiveness in accelerating functional recovery after meniscal and chondral injury to the knee.

The results from our work demonstrate that only a limited number of studies are available, usually of moderate quality. The data suggest a variable effect on cartilage regeneration, and a potential for accelerated functional recovery in gait and running dynamics both with anti-gravity treadmill as well as suspension harness systems.

Keywords : anti-gravity training ; meniscus ; cartilage ; AlterG ; suspension harness ; rehabilitation.

INTRODUCTION

Partial weight bearing is often advised during the rehabilitation after meniscus or cartilage surgery. The aim of weight bearing restriction is to protect the joint from the deleterious effects associated with impact loading, and to allow safe and optimal healing of the tissues.

Several modalities exist to achieve partial weight bearing, including the use of walkers, canes or crutches, the use of parallel bars, therapist assisted waist belts and swimming pools. Despite the widespread use of these systems, they have practical limitations and impede the natural ambulation and motion patterns that are required for optimal and fast return to normal. *(2, 6)*

Recently, anti-gravity training has therefore been introduced as an attractive rehabilitation modality with the purpose to speed up the functional rehabilitation while at the same time protect the

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healing structures from harmful effects associated with impact loading.

Anti-gravity treadmills (AlterG ®) and harness suspension devices are the two most commonly applied techniques.

Anti-gravity treadmills, also called lower body positive pressure treadmills (LBPP), allow normal treadmill walking and running while significantly reducing body weight. These devices use an inflatable space around the lower extremities through which an upward force is applied onto the pelvic girdle, lifting the body of the patient. As such, the ground reaction force can be reduced with increments of 1%, with a maximal reduction of body weight up to 80% *(2).*

Harness suspension devices work through an external harness mounted over a treadmill, lifting the patient at the trunk and at the pelvis through a pneumatic cylinder or a calibrated external lifting mechanism. The subject is supported by the harness while walking or running on the treadmill. The harness is designed to divide the forces acting on the body as large as possible, while providing minimal interference during walking and running *(10,17,21).*

Despite the growing popularity of these devices, it remains unclear how valid the available scientific data are to support their use in the rehabilitation after meniscal or chondral injury of the knee.

The purpose of our study was therefore to perform a systematic literature review both on antigravity and harness suspension devices**,** with respect to (1) their acclaimed advantages in achieving correct walking and running dynamics, (2) as well as on their effects on biological restitution and regeneration after cartilage or meniscal injury.

METHODS

Our systematic review was performed following the instructions and checklists of the "Cochrane Effective Practice and Organisation of Care Review Group".

In January 2016 we searched the databases of Pubmed and Web of Science using the following key words and MeSH-terms : "knee joint", "knee", "cartilage", "cartilage diseases", "cartilage abnormalities", "menisci, tibial", "menisci, tibial/abnormalities", "chondral", "gravity, altered", "antigravity", "antigravity therapy", "antigravity rehabilitation", "alter G". We did not limit on date of publication.

In order to obtain an objective and complete result, two of the authors (N.D and M.L) separately and independently screened the titles and abstracts of the articles to assess whether they met the selection criteria. Afterwards the lists of selected titles were compared and in case of a difference a consensus was made whether to include or not.

Studies included in the selection were searched manually in their reference lists for additional publications that could meet our selection criteria.

The Web of Science Search alert was used to make sure new relevant studies that were published after our first search could be included.

Studies were included when addressing each of the following inclusion criteria :

- Reduced impact loading or antigravity training as intervention
  – Knee joint
  – Cartilage or meniscus
  – Chondral injury
  – Meniscal injury

Studies were excluded when meeting one of the following exclusion criteria :

– No reduced impact loading as intervention
– No knee injury but other pathology examined
– Embryogenic development as study subject
– Evaluating only muscle strength or muscle function as outcome parameter
– Exoskeleton as intervention
– Neurological function as primary outcome

For quality assessment and avoiding of risk of bias, all selected articles were read in their full length for evaluation of the study design. Four studies were found to be reviews. *(3,5,19,22)* Seventeen were quasi-experimental design, not using a control group or randomization *(2,4,6,7,8,9,10,11,12,13,14,15,16,17,20,21,23).* Two studies were considered as randomized controlled trials. *(1,18)* Randomization was done by randomly assigning patients to a group or by randomly assigning the order of intervention to the patient.

The selected quasi-experimental studies were assessed by using the "Modified Cochrane EPOC checklist". As such, each study received a score from zero to five. A total score < 2 was scored as low quality, a score between 2-4 as moderate quality, and a score > 4 as high quality. The selected reviews were assessed using the "Cochrane Review Checklist", with a score < 4 as low quality, between 4-6 moderate quality, with a score > 6 as high quality.

The selected randomized controlled trials were assessed using the "Cochrane RCT checklist", with a total score < 5 being considered as low quality, between 5-8 as moderate quality, and > 8 as high quality.

The score assessment was made by one researcher and checked by the other one.

Data-extraction was performed for each selected publication, and was entered in the data-extraction table (table I), consisting of : author(s), year of publication, study design, patients characteristics, number of participants, mean age and standard deviation, intervention(s) and control, outcome measures, results and conclusions.

RESULTS

122 Potential articles were identified after our electronic literature search, 55 on Pubmed, 57 on Web Of Science, and 10 referenced articles. After analyzing title and abstract, 27 articles potentially fulfilled the inclusion and exclusion criteria. After reading their full-length versions, 23 articles fulfilled the in- and exclusion criteria. (Fig 1)

Results quality

4 Review articles were included, each of low quality (Cochrane Review Checklist score < 4) *(3,5,19,22)*. Absence of proper selection procedure, quality assessment, data-extraction, and statistical analysis contributed to the low scoring.

17 quasi-experimental study fulfilled the criteria. One was scored as low quality *(10)*. The study did not report on secular changes, outcome measures, detection bias and completeness of dataset and follow-up. They did not state a clear research question and follow-up was not long enough. 6 Studies were of moderate quality. *(9,13,14,16,21,23)*

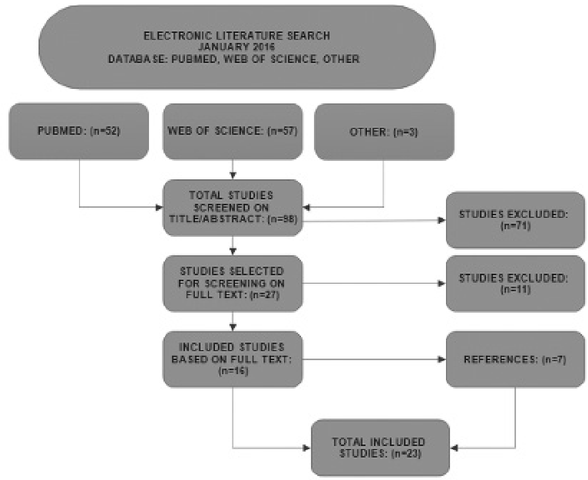

Fig 1. — Flowchart.

Five of these studies did not use a randomized design. Four did not continue follow-up long enough. Ten studies *(2,4,6,7,8,11,12,15,17,20)* were of high quality. Each of these had a randomized design, was protected against secular changes and detection bias, reported on reliable and valid outcome measures, and demonstrated completeness of datasets and follow-up.

Two randomized controlled trials were included, one of low quality *(1)* due to incomplete follow-up, selective publication of results, and possible influence of sponsors. The second RCT was of moderate quality *(18)* and lacked information on blinding procedure.

Data-extraction *(Table 1)*

a. Effects on biological restitution and regeneration after cartilage or meniscal injury.

10 Studies investigated the effect of reduced gravity on cartilage composition and chondrogenesis. No publications could be found on the biological effects of reduced gravity on meniscal tissue or cartilage regeneration after injury.

The included studies demonstrate that chondrogenesis is limited when chondrocyte cultures are placed in reduced gravity at the early stages of chondrogenesis, whereas reduced gravity has a lesser effect on cartilage growth and development at later stages of chondrogenesis. Reduced gravity

Table I. — Data-extraction table

Author Year	Study design	Participants	n	Mean Age ± SD in years	Intervention (+ control)	Outcome measures	Results	Conclusion
Brown, J.L. et al. 2015	RCT	Patients who underwent a primary ACL reconstruction performed by one surgeon and who were admitted at the CORE Institute for rehabilitation	15	32,04 ± 10,18 yr	Intervention: physical therapy with the AlterG Anti-Gravity Treadmill system Control: physical therapy with a standard treadmill	Functional recovery outcomes: biometric measures, gait parameters, clinical scores and length of time	Control group experienced more side effects. There is a positive evolution in the use of the AlterG Treadmill after ACL surgery.	The use of the AlterG Treadmill ensures earlier restoration of function in terms of walking, when comparing this method to physical therapy that uses a standard treadmill.
Cutuk, A., et al. 2006	Quasi exp. design	Healthy male and female subjects, voluntary	15	22-55 yr	9 subjects: noninvasive cardiovascular research while standing and walking in upright LBPP. 6 subjects: gait analyses protocol	Systemic and cardiovascular parameters (heart rate, blood pressure, brain oxygenation, blood-flow velocity, head skin microvascular blood flow) and gait kinematics (GRF, knee and ankle sagittal ROM, stride length)	HR: decreased SBP: increased (not significant) DBP: increased Blood flow velocity: no signifi-cant increase Forehead skin microvasular blood flow: remained unchanged Brain tissue oxygenation: varied, no statistical significance Peak GRF: significant decrease Ankle ROM: no significant chan-ges Knee ROM: no significant chan-ges Stride length: significant increase	LBPP prevents muscle atrophy (that is asso-ciated with bed rest or disuse) and decreases joint forces, protects healing tissues and prosthesis. Also decreases pain with ambula-tion. Allows patients to start walking earlier in their rehabilitation.
De Witt, J.K., et al. 2010	Quasi exp. design	Subjects who were never injured to their lower limbs	5	36,2 ± 2,6 yr	Intervention: walking in simulated micrograviy conditions Control: walking in actual microgravity conditions	Lower body joint kinematics (ROM hip, ROM knee) and GRF	Hip ROM and trunk ROM were greater in the actual microgravity condition. There was more con-tact time in simulated micro-gravity which may cause less stride length.	Subtle differences in locomotion patterns, as well as in temporal kinematics and peak impact GRF between the actual microgravity and simulated microgravity. Walking in simulated microgravity with lower external load could have a stimulating effect on osteogenesis.
Dev K. Mishra, M.D. 2015	Review	Not adequately described	/	Not adequately described	Intervention: use of the AlterG Anti-Gravity Treadmill	Knee injury and Osteoarthritis Outcome Score (KOOS), Timed Up and Go (TUG), pain scores, muscle activation, articular cartilage catabolism, joint pain, joint function, thigh muscle strength and physical function	Rehabilitation with the AlterG Treadmill after total knee arthroplasty enhanced scores on KOOS, TUG and pain. We see a higher articular cartilage breakdown with more body weight. When using the AlterG Treadmill, it is sure that subjects maintain their cardiovascular response although they walk with less knee joint load. When running in the AlterG Treadmill there are improvements in pain and varus thrust. There is no difference for muscle activation of gastrocnemius and tibialis anterior. There is an enhancement of function and pain of the knee joint, with higher thigh muscle strength in overweight participants with knee osteoarthritis. Use of the AlterG Treadmill showed improvements in quadriceps and hamstring muscle strength and functional abilities as well as a reduction in knee osteoarthritis symptoms.	Walking on the AlterG may have a positive effect on pain relief, functional abilities and muscle strength.
Duke, P.J. and D. Montufar-Solis 1999	Review	Cells of rats	/	/	Intervention: microgravity	Chondrogenesis	Microgravity through clinorotation decreases the number of condensations. It is necessary that there is a certain load in the process of chondrogenesis to make sure there is a normal development of the limbs.	In order to make sure there is a proper development of cartilage in the endochondral stage a certain load needs to be present.

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Eastlack, R.K., et al. 2005	Quasi exp. design	Voluntary subjects with unilateral arthroscopic meniscectomy	9	28-73 yr	LBPP testing: 2 minutes of walking at 2 different treadmill speeds under three LBPP conditions.	GRF, EMG (VMO, BF), knee ROM, gait parameters, heart rate, levels exertion and discomfort	LBPP: significant decrease in GRF bilaterally. EMG (peak amplitude): VMO decrease, BF unchanged ROM: significant decrease Gait patterns: no difference Heart rate: significant decrease Perceived exertion: significant decrease Knee pain: less pain in 7 out of 9 patients.	Remarkable reduction in GRF while maintaining normal gait parameters. Some changes in: EMG activity, knee ROM but still significant joint motion and muscle activation. This in combination with decreased heart rate and lower exertion rates. Facilitation in gait recovery and physical rehabilitation, suitable for situations that require decreased lower extremity loading.
Emin, N., et al. 2008	Quasi exp. design	Chondrocytes of rats	/	/	Intervention: microgravity in terms of 3D static and dynamic cultures Control: single cell monolayer (2D)	The effect of seeding conditions on cellularization of the scaffolds	The addition of TGF-β1, which is involved in cartilage development and repair, in chondrocytes cultivated under dynamic conditions harvested a higher cellular density and displayed larger chondrocytes and more antibodies. Chondrocytes originating from rat articular cartilage showed the best neocartilage generation on 3D-PLGA sponges. Cells are better spaced in 3D medium which makes transportation of gas and nutrients easier. It is important for tissue to experience shear stress in order to adapt their mechanical characteristics.	TGF-β1 in combination with 3D culture medium has the most effect on cartilage regeneration.

Freed, L.E., et al. 1997	Quasi exp. design	Chondrocytes from bovine calves	/	/	Intervention: cultivation of cells in space Control: cultivation of cells on earth	Chondrocyte function, construct composition, mechanical behaviour	Cells cultivated in space had a more spherical form than those on earth due to constant pressure and mass transport on all areas. Cells cultivated in space had irregular orientation of collagen more as the construct grown on earth. The construct cultivated on earth had higher wet weights, GAG fractions and aggregate moduli due to forces that act on the cells.	Mechanical stress has a positive effect on certain stages in the development of cartilage.
Freed, L.E. and G. Vunjak-Novakovic, 1997	Quasi exp. design	Chodrocytes from bovine calves	/	/	Intervention: simulated microgravity in a slow turning lateral vessel, solid body rotation in a slow turning lateral vessel, turbulent mixing in spinner flasks, orbital mixing in petridishes	Histological assessment of cell-polymer constructs, measurement of cell number, number of sulfated GAG and collagen	Simulated microgravity within rotating vessels showed the best results in cultivating cartilage in terms of the amount of regenerated tissue mass and GAG.	A hydrodynamically active setting seems to have a positive effect on the chondrogenesis.
Gazzani, F., et al. 2000	Quasi exp. design	Healthy subjects	2	Male: 49 yr Female: 36 yr	44 trials at different BWS/speed combinations	Walking stride time	BWS <40% and velocities higher than 1,5 km/h the curve fits the predertermined relationship. Most discomfort at slow walking and low % BWS, and high BWS with high velocity.	Three important sources of error: the working principle, the friction, the moving masses.
Goldberg, S.R. and S.J. Stanhope 2013	Quasi exp. design	Healthy adult subjects	8	Not mentioned	Intervention: walking on a treadmill with a body weight suspension system	Ankle plantarflexion moment, knee extension moment, knee flexion moment, hip extension moment, hip flexion moment	They noticed an increase in mean peak joint moment with higher walking speed except for the knee-extension moment. The higher body weight support level, the lower moment sensitivity except for knee-extension moment.	Significant interplay between body weight support and walking speed.
Grabowski, A.M. 2010	Quasi exp. design	Healthy volunteer subjects	10	32 ± 7 yr	Walking on force-measuring treadmill enclosed in LBPP device. Each subject: 17 trials over 2 experimental sessions. Each trial 7 minutes long, 3 minutes rest between trials.	Metabolic rates, stance phase duration, GRF	Faster walking with same BW: greater metabolic demands. Same walking velocity with less BW: metabolic demands decreased. At each velocity: net metabolic power decreased linearly, but in less than direct proportion to BW. All fractions of BW: first peak vertical GRF increased, P2 did not change. Subjects: faster velocities at all fractions of BW by increasing stride frequency and stride length. All velocities: both P1 and P2 decreased linearly and proportionally with BW. No significant changes in stride frequency during weight supported compared with normal walking (except: 0.25 BW at 1.0 m/s and 1.5 m/s). Contact time only slightly shorter at smaller fractions of BW.	LBPP reduces the forces acting on the musculoskeletal system and maintains metabolic demand. Also maintained kinematic timing patterns.

Kurz, M.J., et al. 2012	Quasi exp. design	Healthy adults and children	19	Adults: 25 ± 4 yr Children: 13 ±2 yr	Intervention: walking with supported body weight	Knee and ankle joint kinematics	Subjects walking with body weight support had lower total ROM of ankle and knee, which was independent on walking speed. Vastus lateralis muscle was less active when reducing body weight dependent on walking speed. The gastrocnemius muscle was less active with more body weight support independent on walking speed. Activation of antigravity muscles and kinematics of lower limbs was not dependent on age. Using a support system with neoprene shorts seems to be more comfortable.	There is no difference between children and adults in neuromuscular system when responding on body weight support. The interaction between body weight support and walking speed plays an important role in joint ROM and antigravity muscle activity. When walking with a support system there is less ROM in knee and ankle and less activity of antigravity muscles.
Macias, B.R., et al. 2012	Quasi exp. design	Healthy subjects	8	18-30 years	Intervention: intramuscular pressure measurements during upright lower body positive pressure and lower body negative pressure	Leg intramuscular pressure, ground reaction force, instrumented tibial tray force	There is a linear correlation between peak ground reaction forces during exercise and weight bearing. There is a reduction of 40% body weight in waist-deep water and 60% in chest-deep water. When percent body weight increases there is an increase in peak ground reaction force, total peak tibial forces and peak intramuscular forces of the leg.	Walking with lower body positive pressure could have a positive effect on rehabilitation in postoperative patients to prevent muscle atrophy and fibrous tissue contractures after knee surgery. There can be a gradual increase in body weight to adapt tibial knee forces to make sure there is a good healing process.
Montufar-Solis, D., P.J. Duke, and D. D'Aunno 1996	Quasi exp. design	Pathogen-free, female, Sprague-Dawley rats	53	/	Intervention: suspended for all 7 days, suspended with 1h/day at 1,5g, suspended with 2h/day at 1,5g, suspended with 1h/day at 2,6g, suspended with 2h/day at 2,6g, suspended with 2h/day at 1g on ground Control: no treatment	Mean heights from total growth plates	Growth plates were smaller and there was less cell number per zone and total column in hind limbs with reduced load following tail-suspension. The epiphyseal plate is active in a certain range of load. Too much or too little load makes the epiphyseal plate close.	Results indicate that there is a range of pressure in which the epiphyseal growth plate maintains its normal activity.
Ohyabu, Y., et al. 2006	Quasi exp. design	10-day-old Japanese white rabbits	6	10 days old	Intervention: microgravity environment for cells in a rotating wall vessel bioreactor	Glycosaminoglycan/DNA ratio, aggrecan ratio, collagen type I and II ratio and cartilaginous properties	Chondrogenesis of cartilage cells is more pronounced in rotating wall vessel 3D than in static cultures. More chondrocytes can be cultivated from bone marrow cells. Cartilage growth is limited when cultures are placed in the rotating wall vessel at early stages of chondrogenesis, but benefits in later stages whereas it stimulates growth and development.	Important to consider the different stages of chondrogenesis

Patil, S., et al. 2013	Quasi exp. design	Subjects implanted with instrumented knee prosthesis	4	67-80 years	Intervention: walking on a treadmill housed within a lower body positive pressure chamber	Tibiofemoral forces	There were lower peak axial forces at the tibial tray with reduced body weight. Therapy in water is an effective method for rehabilitation, although lower body positive pressure chamber does not influence hydrodynamic and aerodynamic drag. There was a longer stride time and reduced cadence when body weight was supported.	Lower body positive pressure reduces knee forces and seems to be more efficient than water therapy.
Ruckstuhl, H., et al. 2009	RCT	Healthy volunteers (6 female, 6 male)	12	28 ± 3 yr	Walking in three body weight conditions and three different Froude numbers	6 parameters: 4 gait parameters, 1 cardiovascular parameter, 1 comfort parameter	In LBPP and harness following results were found: All decreased significantly: cadence, normalized stride length, duty factor, heart rate Increased significantly: leg angle at touch down In addition, when using harness: there was a decrease in comfort. With higher Froude numbers, there was an increase in : cadence, normalized stride length and heart rate and a decrease in: duty factor, leg angle and comfort.	Unloading at a constant Froude number: gait pattern is changed, LBPP is more appropriate when treating patients with cardiovascular disease and for conditions at high unloading. When comparing LBPP to harness unloading: higher comfort and lower heart rate with LBPP were most remarkable results. There was no difference for the other parameters.
Saibene, F. and A.E. Minetti 2003	Review	Walking humans	/	/	No intervention No control (descriptive study)	This review describes different models of locomotion, biomechanics of complex movements, mechanical paradigms, how we can measure mechanical work, the transition between gaits etc.	Metabolic costs and spontaneous choices when conditions are changed seem to be explained by the mechanical aspects of legged locomotion.	Studying locomotion is continue changed. This is due to more technologically advanced measurement tools, accumulating knowledge (allows us to study more physiologically conditions such as walking in a real environment). There is an interest in building artificial appendages and robots that are capable of coordinated and independent movements. Following the reviewers, it is necessary to recognize the importance of multimedia products in diffusing knowledge about different aspects of locomotion (biomechanical and physiological).
Stamenkovic, V., et al. 2010	Quasi exp. design	Porcine chondrocytes	/	/	Intervention: culturing cells in microgravity during the Flight 7S in the International Space Station, culturing cells in simulated microgravity in a random positioning machine Control: normal gravity (1g)	Histology, immunohistochemistry, quantitative real-time reverse transciptase-polymerase chain reaction and histomorphometric analysis	Microgravity has an impact on chondrogenesis. There is a higher gene expression and protein production of ECM in chondrocytes and mesenchymal stemcells observed in mechanical pressure loading studies. The ratio of collagen type II to type I is higher in chondrocytes in the random positioning machine than in 1g. Chondrocytes cultured in the random positioning machine are similar to native tissue.	Correct translation to protein depends on gravity resulting from the fact that neocartilage tissue formation is nonuniform and there is less extracellular matrix and altered gene expression.

Threlkeld, A.J., et al. 2003	Quasi exp. design	Non-disabled volunteers	17	24.3 ± 3.4 yr	Intervention: treadmill walking at 1.25 m/sec	Temporospatial and kinematic data with various levels of support	Temporospatial and kinematic changes were induced with 50% and 70% body weight support, not with 10% body weight support.	With 50% and 70 body weight support, the gait pattern of unimpaired subjects is changed significantly.
Vunjak-Novakovic, G., et al. 2002	Review	Cells and tissue	/	/	Intervention: microgravity conditions	Structural and functional properties of cartilage	Musculoskeletal tissue can be remodeled trough physical forces and can be impaired by space flight. Chondrocytes removed from cartilage or bone marrow formed large mechanically functional cartilage.	Physical forces have an effect on the growth of cartilage.
Wehland, M., et al. 2015	Quasi exp. design	Human chondrocytes	/	/	Intervention: parabolic flight (first parabola and 31st parabola), vibration and hypergravity	Microarray, quantitative real time polymerase chain reaction analysis	Hypergravity has an effect on cartilage growth, as well as it reduces MMP3, MMP10 and BMP4. There is an expression of vascular endothelial growth factor A when chondrocytes are exposed to mechanical loading. Vibration creates an inflammation of chondrocytes and destabilized cartilage. There was a higher expression of several genes that provide cell motility, structure and integrity; control of cell growth, cell proliferation, cell differentiation and apoptosis.	Apoptotic rate decreases when chondrocytes are exposed to microgravity.

decreases protein content of the extracellular matrix as well as cell density in neocartilage, whereas the ratio of collagen type II to type I expression increases *(5,7,8,9,15, 6,22)*.

One study demonstrated that the apoptotic rate decreases when chondrocytes are exposed to reduced gravity *(23)*.

b. Effects on restoration of walking and running dynamics.

13 Studies investigated the effect of anti-gravity training on walking and running dynamics. 7 of these studied anti-gravity treadmills, 6 used harness suspension devices, and one study used both.

No studies could be found that compare walking or running dynamics after cartilage or meniscal injury using anti-gravity systems versus conventional rehabilitation.

– Anti-gravity treadmills (AlterG ®)

All studies showed that ground reaction force (GRF) and peak knee joint moments are inversely related to LBPP, and proportionally decrease with uplifting body support *(2,6,11,13,17)*.

Variable effects were noted on lower limb range of motion during running on anti-gravity treadmills, with one study *(2)* demonstrating no difference, whereas two other studies *(6,13)* showing a small but significant ($p<0.01$) reduction in total ROM of the lower limb with uplifting body support.

No significant effects on stride length and cadence were noted *(2,6)*.

– Harness suspension devices

No studies documented the influence of harness support systems on GRF or peak knee joint moments. Increased levels of body suspension were associated with a significant ($p<0.01$) decrease in percentage of double limb support time, decreased cadence, decreased maximum hip and knee flexion, and increased stride length during walking and running *(10,17,21)*.

– Comparative studies

Only one study compared the two devices regarding gait characteristics *(18)*. No significant differences were noted. Both anti-gravity treadmill as well as harness suspension devices were associated with decreased cadence, decreased double limb support time, and increased leg angle at touchdown.

DISCUSSION

Anti-gravity training has recently been introduced in the rehabilitation of patients and athletes who recover from musculoskeletal injury or surgery. The concept has gained interest due to the commercial availability of devices that allow anti-gravity training in a daily physiotherapy setting, either by antigravity treadmills or harness suspension devices.

Anti-gravity training seems logical from a theoretical perspective, since it allows the healing structures to be protected from the inadvertent effects of excessive impact loading. As such, its application is especially interesting in conditions that require load protection during rehabilitation, such as cartilage injury or repair, meniscal injury, stress fractures, or other overload injuries of the lower limb.

Although some anecdotal data exist on the application of anti-gravity training after ACL-reconstruction and after total knee arthroplasty, it remained so far unclear how valid the data are that could scientifically support its use after meniscal and chondral injury to the knee *(1,3,17)*.

The results from our systematic literature review however show that only a limited number of studies are available on this subject, and most of them are of moderate quality. The data suggest a variable effect on cartilage regeneration and a potential for accelerated functional recovery in gait and running dynamics, both with anti-gravity treadmill as well as suspension harness systems.

The scientific data suggest that reduced gravity delays chondrogenesis at the very early stages of cell condensation and cell bounding, whereas reduced gravity has a lesser effect on cartilage growth and development at later stages of chondrogenesis, which is more relevant for rehabilitation. Reduced gravity also decreases the protein content of the extracellular matrix as well as cell density in neocartilage, whereas the ratio of collagen type II to type I expression increases *(5,7,9,20,22)*.

One study demonstrated that the apoptotic rate decreases when chondrocytes are exposed to reduced gravity *(23)*.

The data therefore suggest that the effects of reduced gravity on cartilage are variable. Some of the effects seem to impede cartilage qualitative recovery, others - such as the decreased apoptotic rate - are beneficial.

The above is not so surprising. It seems logical in the sense of Wolf's law that a certain load steers biological processes towards strengthening, whereas overloading (hypergravity) has a potentially negative or catabolic effect on tissues.

When extrapolating this towards antigravity training, it seems that load reduction could be associated with the possibility for higher intensity regimens in exercising, without the risk for detrimental or catabolic effects.

Our review demonstrates that anti-gravity treadmills are effective in reducing ground reaction forces (GRF) and peak knee joint moments, with an inverse relation to the applied upward body force.

Although no such data are available for harness suspension devices, it seems logical that the same is true for them, provided that no relaxation of suspension occurs.

Both anti-gravity treadmill as well as suspension harness systems have little influence on normal walking and running dynamics, and can therefore be considered as realistic tools in walking and running recovery.

The observed patterns of decreased double limb support time, decreased cadence, and increased stride length can probably be considered as a tendency towards a more running rather than walking style of ambulation under reduced gravity conditions.

Our study has a number of limitations. The reviewers only checked two databases (Pubmed and Web of Science), and possibly some additional studies could have been found when more databases were checked. Secondly, no studies were excluded when scoring low or poor for quality. We decided not to exclude these because of the limited number of studies available.

As a conclusion, this systematic review demonstrates that only a limited number of studies are available on the effect of anti-gravity training in the rehabilitation of chondral and meniscus injury in the knee, and most of the available studies are of moderate quality. The data suggest a variable effect on cartilage regeneration. Both anti-gravity treadmills as well as suspension harness systems have the potential for accelerated functional recovery in gait and running dynamics. Further high quality studies are however needed to prove that this can be achieved in practice.

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