

Note: this is the final draft of the article:

Hides J, Lambrecht G, Ramdharry G, Cusack R, Bloomberg J, Stokes M.

**Parallels between astronauts and terrestrial patients – taking physiotherapy
rehabilitation “*To Infinity and Beyond*”**

Musculoskelet Sci Pract 2017; 27(Suppl 1): 32-37

In: *Musculoskeletal Science and Practice* Supplement on: “Terrestrial neuro-musculoskeletal
rehabilitation and astronaut reconditioning: reciprocal knowledge transfer”

Guest Editors: Stokes M, Evetts S, Hides J.

Accepted: 5th November 2016 for publication in *Musculoskeletal Science and Practice*

Please use the following link for the final, fully proofed and peer-reviewed journal article
online:

<http://www.sciencedirect.com/science/journal/24687812/27//supp/S1>

In: *Musculoskeletal Science and Practice* Supplement: “Terrestrial neuro-muscular rehabilitation and astronaut reconditioning: reciprocal knowledge transfer”

Guest Editors: Maria Stokes, Simon Evetts, Julie Hides

PARALLELS BETWEEN ASTRONAUTS AND TERRESTRIAL PATIENTS – TAKING
PHYSIOTHERAPY REHABILITATION “TO INFINITY AND BEYOND”

^{1,2}Julie Hides PhD

^{3,4}Gunda Lambrecht Dip Physiotherapy

⁵Gita Ramdharry PhD

^{6,7}Rebecca Cusack MD FFICM

⁸Jacob Bloomberg PhD

^{9,10}Maria Stokes PhD

1. Centre for Musculoskeletal Research, Mary MacKillop Institute for Health Research, Australian Catholic University, Brisbane, Australia, 4102
2. Mater/ACU Back Stability Research Clinic, Mater Health Services, South Brisbane, QLD 4101, Australia
3. European Space Agency Space-Medicine Office, European Astronaut Centre, Linder Hoehe, 51147 Cologne,
4. Germany Praxis fur Physiotherapie und Osteopathische Techniken, Kaiserstrasse 34, 53721 Siegburg, Germany
5. Faculty of Health, Social Science and Education, Kingston University/St George’s University of London, London SW17 0RE
6. Critical Care Research Area, Southampton NIHR Respiratory Biomedical Research Unit, University Hospital NHS Foundation Trust, Southampton SO16 6YD
7. Integrative physiology and Critical Illness Group, Faculty of Medicine, University of Southampton
8. Neuroscience Laboratories, NASA/Johnson Space Center, Houston, Texas, USA
9. Faculty of Health Sciences, Building 45, University of Southampton Highfield Campus, Southampton, SO17 1BJ
10. Arthritis Research UK Centre for Sport, Exercise and Osteoarthritis

Corresponding Author: Professor Julie Hides

Australian Catholic University, Level 1, 631 Stanley Street, Woolloongabba, Australia, Q4102, Email: julie.hides@acu.edu.au

Phone: +617 3623 7530

ABSTRACT

Exposure to the microgravity environment induces physiological changes in the cardiovascular, musculoskeletal and sensorimotor systems in healthy astronauts. As space agencies prepare for extended duration missions, it is difficult to predict the extent of the effects that prolonged exposure to microgravity will have on astronauts. Prolonged bed rest is a model used by space agencies to simulate the effects of spaceflight on the human body, and bed rest studies have provided some insights into the effects of immobilisation and inactivity. Whilst microgravity exposure is confined to a relatively small population, on return to Earth, the physiological changes seen in astronauts parallel many changes routinely seen by physiotherapists on Earth in people with low back pain (LBP), muscle wasting diseases, exposure to prolonged bed rest, elite athletes and critically ill patients in intensive care. The medical operations team at the European Space Agency are currently involved in preparing astronauts for spaceflight, advising on exercises whilst astronauts are on the International Space Station, and reconditioning astronauts following their return. There are a number of parallels between this role and contemporary roles performed by physiotherapists working with elite athletes and muscle wasting conditions. This clinical commentary will draw parallels between changes which occur to the neuromuscular system in the absence of gravity and conditions which occur on Earth. Implications for physiotherapy management of astronauts and terrestrial patients will be discussed.

Key words: Spaceflight, microgravity, reconditioning, rehabilitation, exercise

Highlights

- Neuro-musculoskeletal changes in astronauts parallel changes in patients on Earth
- Motor control training for low back pain patients is applicable to astronauts
- Astronaut reconditioning principles may be relevant to intensive care patients.
- Benefits of exchanging physiotherapy practices between space and Earth are reciprocal

1. Introduction

Physiotherapy is inextricably linked to the effects of gravity on the human body. In the early 1900's, "gravity tests" were developed (Hislop, Avers, & Brown, 2013). In the 1940's, a system for recording muscle dysfunction in people with poliomyelitis was introduced (Hislop et al., 2013) whereby grading of muscle function was accomplished using gravity and manual resistance techniques. Manual muscle testing is still conducted today, and the principles involved underpin much of the theoretical basis of contemporary physiotherapy practice. Another area directly linked with the relationship to gravity on Earth is posture. The line of gravity normally passes through the ventral part of the L3 vertebral body (Richter & Hebgen, 2006), and biomechanical models have shown that the body is best able to withstand compressive forces when positioned in a cervical lordosis, thoracic kyphosis and lumbar lordosis (Kiefer, Shirazi-Adl, & Parnianpour, 1997). Specific muscles are required to maintain posture and the term "postural muscles" was used to describe antigravity muscles which are tonically active.

Neuromuscular plasticity refers to the ability of the nervous system to adapt and change the control and properties of skeletal muscle in response to both therapeutic input and environmental stimuli (Kidd, Lawes, & Musa, 1992). Rapid remodelling of the neuromuscular system occurs in microgravity, with animal studies demonstrating that changes in gravitational or load related cues result in a biased recruitment away from antigravity muscles (Recktenwald et al., 1999). Healthy astronauts undergo specific physiologic changes in microgravity, which, on return to Earth, manifest as physical impairments requiring a period of rehabilitation (Payne, Williams, & Trudel, 2007). Interesting parallels can be drawn between the changes seen in the neuromuscular system induced by microgravity and those seen on Earth. Some changes due to unloading in microgravity are similar to those seen in terrestrial patient populations such as spinal cord, geriatric or deconditioned bed rest patients

(Payne et al., 2007). In addition, conditions such as low back pain (LBP) and exposure to elite sports can also have specific effects on the neuromuscular system which bear some resemblance to changes seen in astronauts. The benefits of exchanging knowledge and expertise between the two environments are therefore reciprocal.

Space agencies are currently preparing for extended duration missions, including exploration of Mars. In addition, more members of the general public may be exposed to microgravity in the future due to increased availability of commercial human spaceflight. Current long duration missions to the International Space Station (ISS) are 6 months long on average. Ultra-long duration space travel, such as interplanetary space travel to Mars, would result in 3 years or more in microgravity. Physiologic adaptation to microgravity is dependent on exposure, with greater levels of disability anticipated on returning to Earth after longer missions (Payne et al., 2007). Combining the knowledge and understanding of the effects of microgravity with the expertise of those involved in rehabilitation is therefore required.

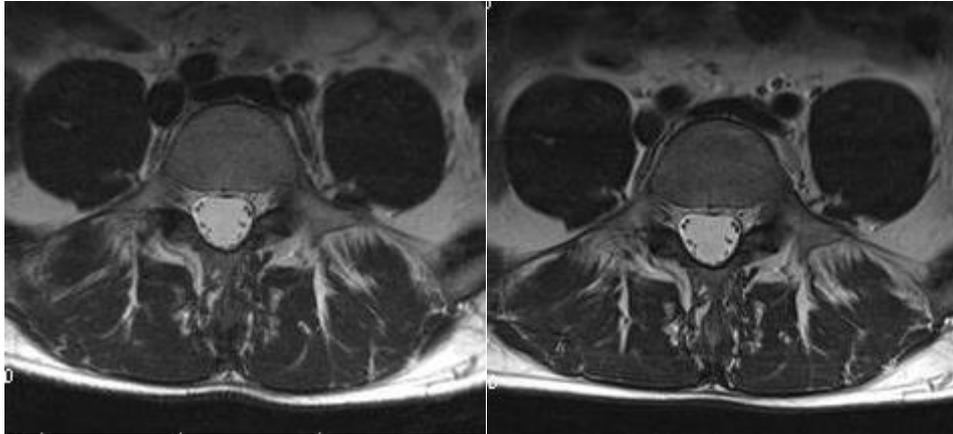
The aims of this clinical commentary are to:

- 1) Outline and discuss conditions on Earth and their physiotherapy management which could inform reconditioning of astronauts.
- 2) Draw parallels between changes which occur to the neuromuscular system in the absence of gravity in both astronauts and the terrestrial population, which could help physiotherapists better understand and prescribe interventions to the patient on Earth and the astronaut involved in spaceflight.

2. Lessons from Prolonged Bed Rest studies

Prolonged bed rest is a model used to simulate the effects of spaceflight on the human body (Nicogossian & Dietlein, 1982). Subjects follow a strict protocol of lying down in bed at a 6 degree head down tilt for days to months.

A 60 day bed rest study (2nd Berlin Bed Rest study- BBR-2) assessed lower limb muscles and showed that the response to bed rest was not uniform (Miokovic, Armbrrecht, Felsenberg, & Belavy, 2012). In the lumbo-pelvic region, increases in disc volume, spinal length, loss of the lower lumbar lordosis, and changes in muscle size occur (Belavy, Armbrrecht, Richardson, Felsenberg, & Hides, 2011). The rate of muscle atrophy was greatest in the multifidus muscle (L4 and L5 vertebral levels) and the lumbar erector spinae (at L1 and L2). In contrast, the size of the psoas muscle at the trunk increased (Belavy et al., 2011; Hides et al., 2007).



(a)

(b)

Figure 1: Transverse Magnetic Resonance Image (MRI) at L4 vertebral level (a) start and (b) end of 60 days bed rest, showing atrophy of the multifidus muscles, but not of the psoas muscles. (MRIs reproduced with permission from Prof D Felsenberg and Dr D Belavy).

Bed rest studies constitute a direct link between space research and rehabilitation medicine (Payne et al., 2007). In the BBR-2, two physiotherapists were provided with a unique opportunity. The European Space Agency (ESA) physiotherapist (Lambrecht et al. 2017) and a physiotherapist experienced in motor control training designed and delivered a reconditioning program. Magnetic resonance imaging (MRI) of the lumbo-pelvic region was conducted at the start and end of bed rest and during the recovery period. After bed rest, participants underwent either trunk flexor and general strength (TFS) training or specific motor control training (MCT). MCT was based on combining the approaches used by the two physiotherapists (Hides, Lambrecht, et al., 2011). Both exercise programs restored the multifidus muscle but further increases in psoas muscle size were seen in the TFS group up to 14 days after bed rest. Results suggest that incorporation of weight bearing exercises in good spinal alignment increased the atrophied multifidus muscles, and decreased the size of the increased psoas muscles.



(a)

(b)

Figure 2. (a) Trunk flexor and general strength (TFS) training and (b) specific motor control training (MCT) following prolonged bed rest.

3. Motor control training for astronauts and terrestrial populations

The ESA approach to post space mission lumbo-pelvic reconditioning has been published (Evetts et al., 2014; Lambrecht et al. 2017; Petersen et al. 2017). Whilst the physiotherapy programme encompassed much more than rehabilitation of the lumbo-pelvic region, a recent case history documented changes in lumbo-pelvic muscles associated with spaceflight (Hides et al. 2017). Results showed that reconditioning post spaceflight restored the sizes of the multifidus and anterolateral abdominal muscles. Data from other astronauts pre and post spaceflight are currently being collected by the ESA medical operations team.

4. Lessons from the patient with low back pain and elite athletes

A similar MCT approach has been used on Earth for people with acute LBP, chronic LBP, elite cricketers and elite Australian Football League players (Hides et al., 1996; Hides et al., 2008; Hides, Stanton, Mendis, Gildea, & Sexton, 2012). The programme has been shown to decrease LBP, was commensurate with decreased games missed due to injury and was predictive of injury (Hides & Stanton, 2016; Hides et al , 2011; Hides, Mendis, et al., 2016; Hides et al, 2014). The program also restored the size of hip muscles such as the gluteus medius, most likely due to performance of weight bearing exercises in good femoropelvic alignment (Mendis & Hides, 2016). The FIFA 11+ used as a warm-up by football (soccer) players is perhaps the most widely implemented neuromuscular exercise injury prevention programme currently used (Soligard et al. 2010). More targeted preventive training programmes are now being developed for specific sports and occupational cohorts (Padua et al., 2014).

Movement screening in the elite athlete comprises two types of tests: physical performance tests, which assess function and provide objective (quantitative) data, e.g. Triple Single Leg Hop, Star Excursion Balance Test (Hegedus et al 2014; 2015), and movement control tests, which assess quality of movement and provide qualitative observation data. Movement control tests identify and rate functional compensations, asymmetries, impairments or efficiency of movement control through transitional (e.g. single knee bend, squat, sit-stand, lunge) or dynamic (hopping, walking, landing, cutting) movements tasks. Several movement control screening tools exist, e.g. the functional movement screen or FMS (Kiesel et al., 2007) the Nine Test Screening Battery (Frohm et al., 2011) and the Performance Matrix (Mottram & Comerford 2008). However, consensus is needed to harmonise terminology and definitions used (Teyhen et al 2014; Hegedus et al 2015) and further research required for movement tests to be implemented in pre- and post- spaceflight screening.

5. Lessons from rehabilitation in intensive care

Survivors of critical illness experience significant deconditioning which can have detrimental effects on quality of life for years after recovery (Herridge et al., 2011). The well-known consequences of bed rest are compounded in critically ill patients by systemic inflammation associated with sepsis resulting in up to 12% muscle loss within the first week of illness (Puthuchery et al., 2013). Further heavy sedation and use of neuromuscular blocking drugs can induce complete ‘mechanical silence’ of the muscles. Physiotherapy for critically ill patients needs to start early to prevent deconditioning. Choice of therapy depends primarily on the patient’s level of consciousness, whether they have volitional movement and whether they are able to follow instructions. If able the patients are engaged in increasingly demanding active interventions. If patients are unable to actively participate they receive passive interventions (Gosselink et al., 2008; Sommers et al., 2015) in an effort to maintain joint range of movement and prevent muscle loss. Very early rehabilitation (within 2-5 days

of critical illness) attempts to attenuate this rapid deconditioning and has focused on non-volitional mobility therapy. Studies applying unilateral continuous passive movement (daily for 9-10 hours over 7-10 days) in sedated critically ill patients can preserve muscle architecture, reduce protein loss (Griffiths et al., 1994) and help preserve force generation capacity of muscle (Ilano-Diez et al., 2012). The introduction of cycle ergometry into intensive care units (ICUs) means that both passive and active cycling can be implemented from the very early stages of illness (Piers-Neto et al., 2013, Burtin et al., 2009).



Figure 3: Cycle ergometry, including passive and active movements, is useful within the very early stages of critical illness (with permission).

Neuromuscular electrical stimulation (NEMS) creates passive contraction of skeletal muscle. Its use increases muscular blood flow, oxidative capabilities and maximal force generation capacity (Bax et al., 2005). Similar effects are seen in the critically ill with

preserved muscle mass (Gerovasili et al., 2009), improved function and improved microcirculation (Gerovasili et al., 2009), which has been shown to have both local and systemic effects (Routsi et al., 2010). In chronically ventilated patients mobility therapy with NEMS results in significantly improved muscle strength compared to those who receive standard mobility therapy alone (Zanotti et al., 2003), although these effects have not yet been reproduced in the critically ill (Kho et al., 2015). A potential alternative to NEMS is functional electrical stimulation (FES) which differs from NEMS in that it stimulates muscles in functional patterns. FES in conjunction with cycle ergometry may be potentially beneficial to patients who are not able to partake in volitional exercise (Parry et al., 2014). Investigations as to whether this is beneficial alone or in conjunction with applied resistance are in development. Attempts to counter the chronic loss of neuromuscular function and performance in association with prolonged exposure to microgravity might benefit from considering modified use of some of the positive techniques in development in intensive care rehabilitation practice today.

6. Lessons from Rehabilitation of Muscle Wasting Diseases (Neuromuscular Diseases)

A number of the changes in the neuromusculoskeletal and sensorimotor systems seen after spaceflight or prolonged bed rest are similar to the secondary deconditioning effects seen in people with neurological disorders.

6.1 Muscle atrophy

People with neuromuscular diseases (NMDs) experience marked atrophy and weakness caused by diseases of the anterior horn cell, peripheral nerves, or muscle tissue. MRI studies exploring primary and secondary muscle atrophy in NMDs has

enabled greater understanding of the mechanism of weakness and muscle function in this group. In primary muscle atrophy there is replacement with fat tissue due to muscle fibre necrosis or long term denervation (Morrow et al., 2015). Similar fatty infiltration has also been observed with aging (Hogrel et al., 2015). People with NMDs tend to be sedentary and volume loss is also observed in muscles not affected by the primary disease, with associated reduced muscle strength (Morrow et al., 2015). This is thought to be secondary, disuse atrophy and is a key focus of rehabilitation programmes in conditions where there is no reversal or treatment of the disease process (Ramdharry et al., 2010). Secondary atrophy tends to be chronic and long term, so may be a good model for comparison with microgravity induced deconditioning.

6.2 Sensory impairment

People with polyneuropathies commonly experience sensory impairment, particularly of proprioception (van der Linden et al., 2010). Transcranial magnetic stimulation suggests that NMDs with sensory impairment may have reduced central activation, implying central changes to the sensory pathways where there has been limited feedback (Schillings et al., 2007). This has implications for astronauts who may experience central changes due to altered sensory feedback. Central reinterpretation of sensory input impacts postflight gait and balance (Mulavara et al., 2010; Wood et al., 2015). Altered proprioceptive feedback can affect joint moments and power generation during gait, plus poor postural stability and increased visual dependency (Mazzaro et al., 2005; van der Linden et al., 2010.)

6.3 Fatigue and fatigability

Fatigue and fatigability have specific definitions. A common way of describing types of fatigue use the following categories: physiological (peripheral) and central fatigue

(Taylor & Gandevia, 2008) though experienced fatigue has also been described in relation to people with NMDs (Schillings et al., 2007). Fatigue in NMDs and other neurological conditions is known to be multi-factorial (Schillings et al., 2007; Kalkman et al., 2007) and may be of more concern for astronauts in long duration missions than current ISS missions.

Strategies used in people with neuromuscular diseases (NMDs), may have relevance to space rehabilitation. A relevant comparison may be rehabilitation of chronic secondary disuse and deconditioning in the less affected muscles groups/ sensory systems of people with lifelong NMDs. A number of studies have investigated both strength and cardiovascular training protocols for a spectrum of nerve and muscle diseases. For strength training, significant effects were observed with 16 to 24 week programmes using standard protocols recommended by the American College of Sports Medicine (Ramdharry et al. 2014; Lindeman et al., 1995). It is worth considering that the effect sizes to achieve functional improvement in these chronic, long term conditions may be a lot smaller than those required by astronauts to get back to pre-flight levels. An additional in-flight countermeasure that could be considered for such muscle groups is electrical stimulation. It has been explored in critical illness polyneuropathy and critical illness myopathy, and is used in the Russian space programme, however its efficacy is yet to be fully established (Hermans et al., 2014).

Rehabilitation strategies which challenge the sensorimotor control systems have also been explored in polyneuropathies. Small exploratory studies of moving and vibrating platforms show some potential in patients with neuropathy (Yoosefinejad et al., 2015) and vestibular dysfunction (Nardone et al. 2010). Vibrating insoles have also showed improvements in balance parameters in people with diabetic peripheral neuropathy (Ites et al., 2011).

Functional and exercise training have also shown benefits in patients with neuropathy, including Tai Chi showing improvements in balance (Ahn & Song, 2012), proprioceptive balance training as part of mixed programmes that include lower limb strengthening (Ites et al., 2011) and improvements in laboratory based balance measures after multi-sensory balance training (Missaoui & Thoumie, 2013). It would appear that functional training requires several weeks to demonstrate change, but some of the higher tech approaches may give faster results. The studies to date are small, however, and we must still consider the differences in effect size required for people with NMDs to show functional improvement, and the effect size required for astronauts to return to pre-flight function.

Progressive muscular atrophy in microgravity has been documented by several researchers (diPrampo & Narici 2003; Fitts et al., 2000; Akima et al., 2000; Riley, 1999, Riley, 2000; Vandenberg, 1999; Leblanc et al., 1995). Without countermeasures, muscle mass has been shown to plateau at two thirds of the initial mass after about 270 days (diPrampo & Narici 2003). Atrophy has been shown to be greatest in postural antigravity muscles (diPrampo & Narici 2003; Fitts et al., 2000; Tesch et al 2005). NMDs that are “single incident” and undergo full or partial recovery provide some parallels with deconditioning in astronauts, e.g. Guillain Barre syndrome (GBS), critical illness polyneuropathy (CIP) and critical illness myopathy (CIM). Recovery from these conditions, however, also relies on recovery from a pathological process and can take several months, so direct application to astronauts may be limited. Nevertheless, parallels with space rehabilitation may become more relevant for longer missions.

7. Conclusions

So what do elite athletes, people with LBP and other neuromuscular conditions on Earth have in common with astronauts? There are many parallels which can be drawn, and research on astronauts and terrestrial people is reciprocal and mutually beneficial. This clinical commentary has endeavoured to outline and discuss conditions on Earth and their physiotherapy management which could inform reconditioning of astronauts. In addition, drawing parallels between changes which occur to the neuromuscular system in the absence of gravity could help physiotherapists better understand interventions for the terrestrial population. Only the future can tell whether lessons learned on Earth will ultimately assist the astronauts to go to and return from “infinity and beyond”...

ACKNOWLEDGEMENTS

The authors thank the European Space Agency (ESA) Post-mission Exercise (Reconditioning) Topical Team for helpful discussions (see Stokes et al., 2017 for team members) and ESA for funding meetings of the Topical Team (Grant ref no: 22930/09/NL/VJ)

REFERENCES

- Ahn S, Song R. Effects of Tai Chi Exercise on glucose control, neuropathy scores, balance, and quality of life in patients with type 2 diabetes and neuropathy. *J Alternat Complement Med* 2012; **18**: 1172-1178.
- Akima H, Kawakami Y, Kubo K, et al: Effect of shortduration spaceflight on thigh and leg muscle volume. *Med Sci Sports Exerc* 2000;32:1743–7
- Bax L, Staes F, Verhagen A. Does neuromuscular electrical stimulation strengthen the quadriceps femoris? *Sports Medicine*. 2005; **35**: 191-212.
- Belavy, D. L., Armbrecht, G., Richardson, C. A., Felsenberg, D., & Hides, J. A. (2011). Muscle atrophy and changes in spinal morphology: is the lumbar spine vulnerable after prolonged bed-rest? *Spine (Phila Pa 1976)*, *36*(2), 137-145.
doi:10.1097/BRS.0b013e3181cc93e8
- Burtin C, Clerckx B, Robbeets C, Ferdinande P, Langer D, Troosters T, Hermans G, Decramer M, Gosselink R. Early exercise in critically ill patients enhances short-term functional recovery*. *Critical care medicine*. 2009; **37**: 2499-2505.
- diPrampo PE, Narici MV: Muscles in microgravity: From fibres to human motion. *J Biomech* 2003;36:403–12
- Evetts, S. N., Caplan, N., Debuse, D., Lambrecht, G., Damann, V., Petersen, N., & Hides, J. (2014). Post space mission lumbo-pelvic neuromuscular reconditioning: a European perspective. *Aviat Space Environ Med*, *85*(7), 764-765.
- Fitts RH, Riley DR, Widrick JJ: Physiology of a microgravity environment invited review: Microgravity and skeletal muscle. *J Appl Physiol* 2000;89:823–39
- Frohm A, Heijne A, Kowalski J, Svensson P, Myklebust G. A nine-test screening battery for athletes: a reliability study. *Scandinavian journal of medicine & science in sports*. 2012:

- Gerovasili V, Stefanidis K, Vitzilaios K, Karatzanos E, Politis P, Koroneos A, Chatzimichail A, Routsis C, Roussos C, Nanas S. Electrical muscle stimulation preserves the muscle mass of critically ill patients: a randomized study. *Crit Care*. 2009; **13**: R161.
- Griffiths RD, Palmer T, Helliwell T, MacLennan P, MacMillan RR. Effect of passive stretching on the wasting of muscle in the critically ill. *Nutrition (Burbank, Los Angeles County, Calif)*. 1994; **11**: 428-432.
- Gosselink R, Bott J, Johnson M, Dean E, Nava S, Norrenberg M, Schönhofer B, Stiller K, Van de Leur H, Vincent JL. Physiotherapy for adult patients with critical illness: recommendations of the European Respiratory Society and European Society of Intensive Care Medicine Task Force on physiotherapy for critically ill patients. *Intensive care medicine*. 2008; **34**: 1188-1199.
- Hegedus EJ, McDonough S, Bleakley C, Cook CE, Baxter GD. Clinician-friendly lower extremity physical performance measures in athletes: a systematic review of measurement properties and correlation with injury, part 1. The tests for knee function including the hop tests. *British journal of sports medicine*. 2014: bjsports-2014-094094.
- Hegedus EJ, McDonough SM, Bleakley C, Baxter D, Cook CE. Clinician-friendly lower extremity physical performance tests in athletes: a systematic review of measurement properties and correlation with injury. Part 2—the tests for the hip, thigh, foot and ankle including the star excursion balance test. *British journal of sports medicine*. 2015:
- Hermans G, De Jonghe B, Bruyninckx F, Van den Berghe G. Interventions for preventing critical illness polyneuropathy and critical illness myopathy. *The Cochrane database of systematic reviews*. 2014: **1**.
- Herridge MS, Tansey CM, Matté A, Tomlinson G, Diaz-Granados N, Cooper A, Guest CB, Mazer CD, Mehta S, Stewart TE. Functional disability 5 years after acute respiratory distress syndrome. *New England Journal of Medicine*. 2011; **364**: 1293-1304

- Hides, J., & Stanton, W. (2016). Predicting football injuries using size and ratio of the multifidus and quadratus lumborum muscles. *Scandinavian Journal of Medicine and Science in Sports*(Article in press).
- Hides, J. A., Belavy, D. L., Stanton, W., Wilson, S. J., Rittweger, J., Felsenberg, D., & Richardson, C. A. (2007). Magnetic resonance imaging assessment of trunk muscles during prolonged bed rest. *Spine (Phila Pa 1976)*, *32*(15), 1687-1692.
doi:10.1097/BRS.0b013e318074c386
- Hides, J. A., Brown, C. T., Penfold, L., & Stanton, W. R. (2011). Screening the lumbopelvic muscles for a relationship to injury of the quadriceps, hamstrings, and adductor muscles among elite Australian Football League players. *J Orthop Sports Phys Ther*, *41*(10), 767-775. doi:10.2519/jospt.2011.3755
- Hides, J. A., Lambrecht, G., Richardson, C. A., Stanton, W. R., Ambrecht, G., Pruett, C., Belavy, D. L. (2011). The effects of rehabilitation on the muscles of the trunk following prolonged bed rest. *Eur Spine J*, *20*(5), 808-818. doi:10.1007/s00586-010-1491-x
- Hides, J. A., Lambrecht, G., Stanton, W. R., & Damann, V. (2016). Changes in multifidus and abdominal muscle size in response to microgravity: possible implications for low back pain research. *Eur Spine J*, *25 Suppl 1*, 175-182. doi:10.1007/s00586-015-4311-5
- Hides, J. A., Mendis, M. D., Franettovich Smith, M. M., Miokovic, T., Cooper, A., & Low Choy, N. (2016). Association between altered motor control of trunk muscles and head and neck injuries in elite footballers - An exploratory study. *Man Ther*, *24*, 46-51.
doi:10.1016/j.math.2016.05.001
- Hides, J. A., Richardson, C. A., & Hodges, P. W. (2004). Local segmental control In C. A. Richardson, P. W. Hodges, & J. A. Hides (Eds.), *Therapeutic exercise for lumbo-pelvic stabilization: A motor control approach for the treatment and prevention of low back pain* (2nd ed., pp. 185-220). Edinburgh: Churchill Livingstone.

- Hides, J. A., Richardson, C. A., & Jull, G. A. (1996). Multifidus muscle recovery is not automatic after resolution of acute, first-episode low back pain. *Spine (Phila Pa 1976)*, *21*(23), 2763-2769.
- Hides, J. A., Richardson, C. A., & Jull, G. A. (1998). Use of real-time ultrasound imaging for feedback in rehabilitation. *Manual Therapy*, *3*(3), 125-131.
doi:[http://dx.doi.org/10.1016/S1356-689X\(98\)80002-7](http://dx.doi.org/10.1016/S1356-689X(98)80002-7)
- Hides, J. A., Stanton, W. R., McMahon, S., Sims, K., & Richardson, C. A. (2008). Effect of stabilization training on multifidus muscle cross-sectional area among young elite cricketers with low back pain. *J Orthop Sports Phys Ther*, *38*(3), 101-108.
doi:10.2519/jospt.2008.2658
- Hides, J. A., Stanton, W. R., Mendis, M. D., Franettovich Smith, M. M., & Sexton, M. J. (2014). Small Multifidus Muscle Size Predicts Football Injuries. *Orthopaedic Journal of Sports Medicine*, *2*(6), 2325967114537588. doi:10.1177/2325967114537588
- Hides, J. A., Stanton, W. R., Mendis, M. D., Gildea, J., & Sexton, M. J. (2012). Effect of motor control training on muscle size and football games missed from injury. *Med Sci Sports Exerc*, *44*(6), 1141-1149. doi:10.1249/MSS.0b013e318244a321
- Hislop, H., Avers, D., & Brown, M. (2013). *Daniels and Worthingham's muscle testing: Techniques of manual examination and performance testing*: Elsevier Health Sciences.
- Hogrel J-Y, Barnouin Y, Azzabou N, Butler-Browne G, Voit T, Moraux A, Leroux G, Behin A, McPhee JS, Carlier PG. NMR imaging estimates of muscle volume and intramuscular fat infiltration in the thigh: variations with muscle, gender, and age. *Age*. 2015; **37**: 1-11.
- Ites KI, Anderson EJ, Cahill ML, Kearney JA, Post EC, Gilchrist LS. Balance interventions for diabetic peripheral neuropathy: a systematic review. *J Geriatric Phys Ther* 2011; **34**: 109-116.

Kalkman JS, Schillings ML, Zwarts MJ, van Engelen BG, Bleijenberg G. The development of a model of fatigue in neuromuscular disorders: a longitudinal study. *Journal of psychosomatic research*. 2007; **62**: 571-579.

Kho ME, Truong AD, Zanni JM, Ciesla ND, Brower RG, Palmer JB, Needham DM. Neuromuscular electrical stimulation in mechanically ventilated patients: a randomized, sham-controlled pilot trial with blinded outcome assessment. *Journal of critical care*. 2015; **30**: 32-39.

Kidd, G., Lawes, N., & Musa, I. (1992). *Understanding neuromuscular plasticity: a basis for clinical rehabilitation*: Edward Arnold.

Kiesel K, Plisky PJ, Voight ML. Can serious injury in professional football be predicted by a preseason functional movement screen. *N Am J Sports Phys Ther*. 2007

Kiefer, A., Shirazi-Adl, A., & Parnianpour, M. (1997). Stability of the human spine in neutral postures. *Eur Spine J*, 6(1), 45-53. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3454628/pdf/586_2005_Article_BF01676574.pdf

Knott, M., & Voss, D. E. (1968). Proprioceptive neuromuscular facilitation: patterns and techniques. Hoeber Medical Division, Harper & Row.

Lambrecht G, Petersen N, Weerts G, Evetts S, Stokes M, Hides J. The role of Physiotherapy in the European Space Agency strategy for preparation and reconditioning of astronauts before and after long-duration space flight. *Musculoskelet Sci Pract* 2017; 27(Suppl 1): 15-22. <http://www.sciencedirect.com/science/journal/24687812/27//supp/S1>

LeBlanc A., rowe, R., Schneider, V., Evans., H., Hedrick, T., :Regional muscle loss after short duration spaceflight. *Aviat Space Environ Med* 1995; 66:1151-4

Lindeman E, Leffers P, Spaans F, Drukker J, Reulen J, Kerckhoffs M, Köke A. Strength training in patients with myotonic dystrophy and hereditary motor and sensory

- neuropathy: a randomized clinical trial. *Archives of physical medicine and rehabilitation*. 1995: **76**: 612-620.
- Llano-Diez M, Renaud G, Andersson M, Marrero HG, Cacciani N, Engquist H, Corpeño R, Artemenko K, Bergquist J, Larsson L. Mechanisms underlying ICU muscle wasting and effects of passive mechanical loading. *Crit Care*. 2012: **16**: R209.
- Mazzaro N, Grey MJ, Sinkjær T, Andersen JB, Pareyson D, Schieppati M. Lack of on-going adaptations in the soleus muscle activity during walking in patients affected by large-fiber neuropathy. *Journal of neurophysiology*. 2005: **93**: 3075-3085.
- McCloskey, D. I. (1978). Kinesthetic sensibility. *Physiological Reviews*, 58(4), 763-820.
- Mendis MD, Hides JA. Effect of motor control training on hip muscles in elite football players with and without low back pain. *J Sci Med Sport*. 2016 Mar 3. pii: S1440-2440(16)00053-0. doi: 10.1016/j.jsams.2016.02.008. [Epub ahead of print] PubMed PMID: 27012726.
- Miokovic, T., Armbrecht, G., Felsenberg, D., & Belavy, D. L. (2012). Heterogeneous atrophy occurs within individual lower limb muscles during 60 days of bed rest. *J Appl Physiol* (1985), 113(10), 1545-1559. doi:10.1152/jappphysiol.00611.2012
- Missaoui B, Thoumie P. Balance training in ataxic neuropathies. Effects on balance and gait parameters. *Gait & posture*. 2013: **38**: 471-476.
- Morrow JM, Sinclair CD, Fischmann A, Machado PM, Reilly MM, Yousry TA, Thornton JS, Hanna MG. MRI biomarker assessment of neuromuscular disease progression: a prospective observational cohort study. *The Lancet Neurology*. 2016: **15**: 65-77.
- Mottram S, Comerford M. A new perspective on risk assessment. *Physical Therapy in Sport*. 2008: **9**: 40-51.

- Mulavara AP, Feiveson A, Feidler J, Cohen HS, Peters BT, Miller CA, Brady R, Bloomberg JJ. Locomotor function after long-duration space flight: Effects and motor learning during recovery. *Exp Brain Res* 2010; 202(3): 649-59.
- Nardone A, Godi M, Artuso A, Schieppati M. Balance rehabilitation by moving platform and exercises in patients with neuropathy or vestibular deficit. *Archives of Physical Medicine and Rehabilitation*. 2010; **91**: 1869-1877.
- Nicogossian, A. E., & Dietlein, L. F. (1982). Microgravity Simulation and Analogues. In A. E. Nicogossain (Ed.), *Space Physiology and Medicine* (pp. 240-248). Philadelphia, PA: Lea & Febbiger.
- Padua DA, Frank B, Donaldson A, de la Motte S, Cameron KL, Beutler AI, DiStefano LJ, Marshall SW. Seven steps for developing and implementing a preventive training program: lessons learned from JUMP-ACL and beyond. *Clinics in sports medicine*. 2014; **33**: 615-632.
- Parry SM, Berney S, Warrillow S, El-Ansary D, Bryant AL, Hart N, Puthucheary Z, Koopman R, Denehy L. Functional electrical stimulation with cycling in the critically ill: a pilot case-matched control study. *Journal of critical care*. 2014; **29**: 695. e691-695. e697.
- Payne, M. W., Williams, D. R., & Trudel, G. (2007). Space flight rehabilitation. *Am J Phys Med Rehabil*, 86(7), 583-591. doi:10.1097/PHM.0b013e31802b8d09
- Petersen N, Lambrecht G, Scott J, Hirsch N, Stokes M, Mester J. Postflight reconditioning for European Astronauts – a case report of recovery after six months in space. *Musculoskelet Sci Pract* 2017; 27(Suppl 1): 23-31
<http://www.sciencedirect.com/science/journal/24687812/27//supp/S1>
- Pires-Neto RC, Kawaguchi YMF, Hirota AS, Fu C, Tanaka C, Caruso P, Park M, Carvalho CRR. Very early passive cycling exercise in mechanically ventilated critically ill patients: physiological and safety aspects-a case series. *PloS one*. 2013; **8**: e74182.

- Puthucheary ZA, Rawal J, McPhail M, Connolly B, Ratnayake G, Chan P, Hopkinson NS, Phadke R, Dew T, Sidhu PS. Acute skeletal muscle wasting in critical illness. *Jama*. 2013; **310**: 1591-1600.
- Ramdharry GM, Pollard A, Anderson C, Laurá M, Murphy SM, Dudzicz M, Dewar EL, Hutton E, Grant R, Reilly MM. A pilot study of proximal strength training in Charcot-Marie-Tooth disease. *Journal of the Peripheral Nervous System*. 2014; **19**: 328-332.
- Recktenwald, M. R., Hodgson, J. A., Roy, R. R., Riazanski, S., McCall, G. E., Kozlovskaya, I., . . . Edgerton, V. R. (1999). Effects of spaceflight on rhesus quadrupedal locomotion after return to 1G. *Journal of neurophysiology*, *81*(5), 2451. Retrieved from <http://jn.physiology.org/content/jn/81/5/2451.full.pdf>
- Richardson, C. A., & Hides, J. A. (2004). Closed chain segmental control In C. A. Richardson, P. W. Hodges, & J. A. Hides (Eds.), *Therapeutic exercise for lumbopelvic stabilisation: A motor control approach for the treatment and prevention of low back pain* (2nd ed., pp. 221-232). Edinburgh: Churchill Livingstone.
- Richter, P., & Hebgen, E. (2006). Das biomechanische Modell von John Martin Littlejohn – Die Mechanik der Wirbelsaeule *Triggerpunkte und Muskelfunktionsketten* (pp. 59): Hippokrates.
- Riley DA: Is skeletal muscle ready for long-term spaceflight and return to gravity?. *Adv Space Biol Med* 1999;7:31–48
- Riley DA, Bain JL, Thompson JL, et al: Decreased thin filament density and length in human atrophic soleus muscle fibers after spaceflight. *J Appl Physiol* 2000;88:567–72
- Routsis C, Vasileiadis I, Karatzanos E, Pitsolis T, Tripodaki E, Markaki V, Zervakis D, Nanas S, Gerovasili V. Electrical Muscle Stimulation Prevents Critical Illness Polyneuromyopathy. A Randomized Intervention Trial. *American journal of respiratory and critical care medicine*. 2010; **181**: A5099.

- Schillings M, Kalkman J, Janssen H, Van Engelen B, Bleijenberg G, Zwarts M. Experienced and physiological fatigue in neuromuscular disorders. *Clinical neurophysiology*. 2007; **118**: 292-300.
- Soligard, T., Nilstad, A., Steffen, K., Myklebust, G., Holme, I., Dvorak, J., Bahr, R., Andersen, T.E. (2010). Compliance with a comprehensive warm-up programme to prevent injuries in youth football. *Br J Sports Med*, *44*, 787-793
- Stokes M, Evetts S, Hides J. Guest Editorial ‘Terrestrial neuromuscular rehabilitation and astronaut reconditioning: reciprocal knowledge transfer Supplement Issue of *Musculoskelet Sci Pract* 2017; 27(Suppl1): 1-4
<http://www.sciencedirect.com/science/journal/24687812/27//supp/S1>
- Taylor JL, Gandevia SC. A comparison of central aspects of fatigue in submaximal and maximal voluntary contractions. *Journal of applied physiology*. 2008; **104**: 542-550.
- Tesch PA, Berg HE. Effects of spaceflight on muscle. *Journal of gravitational physiology : a journal of the International Society for Gravitational Physiology*. 1998; **5**: P19-22.
- Teyhen D, Bergeron MF, Deuster P, Baumgartner N, Beutler AI, Sarah J, Jones BH, Lisman P, Padua DA, Pendergrass TL. Consortium for health and military performance and American College of Sports Medicine Summit: Utility of functional movement assessment in identifying musculoskeletal injury risk. *Current Sports Medicine Reports*. 2014; **13**: 52-63.
- van der Linden MH, van der Linden SC, Hendricks HT, van Engelen BG, Geurts AC. Postural instability in Charcot-Marie-Tooth type 1A patients is strongly associated with reduced somatosensation. *Gait & posture*. 2010; **31**: 483-488.
- Vandenburgh H, Chromiak J, Shansky J, Del Tatto M, Lemaire J: Space travel directly induces skeletal muscle atrophy. *FASEB J* 1999;13:1031–8

Wood SJ, Paloski WH, Clark JB. Assessing sensorimotor function following ISS with computerized dynamic posturography. *Aerosp Med Hum Perform* 2015; 86(12 Suppl): A45-53.

Yoosefinejad AK, Shadmehr A, Olyaei G, Talebian S, Bagheri H, Mohajeri-Tehrani MR. Short-term effects of the whole-body vibration on the balance and muscle strength of type 2 diabetic patients with peripheral neuropathy: a quasi-randomized-controlled trial study. *Journal of Diabetes & Metabolic Disorders*. 2015; **14**: 1.

Zanotti E, Felicetti G, Maini M, Fracchia C. Peripheral muscle strength training in bed-bound patients with COPD receiving mechanical ventilation: effect of electrical stimulation. *CHEST Journal*. 2003; **124**: 292-296.

Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk a prospective biomechanical-epidemiologic study. *The American journal of sports medicine*. 2007; **35**: 1123-1130.