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Postural muscle atrophy prevention and recovery and bone remodelling through high frequency proprioception for astronauts

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Abstract

The difficulty in applying active exercises during space flights increases the importance of passive countermeasures, but coupling load and instability remains indispensable for generating high frequency (HF) proprioceptive flows and preventing muscle atrophy and osteoporosis. The present study, in microgravity conditions during a parabolic flight, verified whether an electronic system, composed of a rocking board, a postural reader and a bungee-cord loading apparatus creates HF postural instability comparable to that reachable on the Earth. Tracking the subject, in single stance, to real-time visual signals is necessary to obtain HF instability situations. The bungee-cord loading apparatus allowed the subject to manage the 81.5% body weight load (100% could easily be exceeded). A preliminary training programme schedule on the Earth and in space is suggested. Comparison with a pathological muscle atrophy is presented. The possibility of generating HF proprioceptive flows could complement current countermeasures for the prevention and recovery of muscle atrophy and osteoporosis in terrestrial and space environments. These exercises combine massive activation of spindles and joint receptors, applying simultaneously HF variations of pressure to different areas of the sole of the foot. This class of exercises could improve the effectiveness of current countermeasures, reducing working time and fatigue.

Keywords: Microgravity; Postural control; Sport; Entropy; Osteoporosis; Load; Rocking board

1. Introduction

Current countermeasures for negative effects of weightlessness consist of physical exercises and loading suits, designed to load the musculoskeletal structures through the activation of proprioceptive and weight-bearing systems, in order to preserve postural and motor functions [1]. The difficulty in applying active countermeasures (physical exercises) at appropriate intensity and volume has prompted the search for new passive countermeasures, easier to put into practice. Investigations on humans during space flights of varying duration, research in dry immersion [2], ground-based simulation studies [3] and experiments on animals (hindlimb unloading model) [4] have shown that support afferences from the sole of the foot play an important role in the maintenance of the activity of the tonic motor units of the leg muscles (soleus, gastrocnemius). Nevertheless, active exercises are indispensable. Even if the activation of the tonic motor units of a district is possible, as demonstrated, only the need to manage a high

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frequency (HF) sequence of different biomemechanical situations can cause a global, maximal and coordinated intervention of the postural muscles. The present study hypothesizes a new class of tests and training exercises to complement the current methodology, with the aim of improving its effectiveness and reducing working time and fatigue. These exercises are able to activate HF proprioceptive flows from the spindles of all the muscles involved in postural control, applying at the same time pressure to the sole of the foot with the rolling support.

2. Gravity and instability

We have studied antigravity movements in many functional human conditions (from children to world champion athletes of different sport disciplines [5], to severe orthopaedic and neurological pathologies, to disabled subjects like paraplegic subjects, amputees, blind from birth or acquired blind people, subjects with congenital absence of labyrinths, etc.). It is commonly believed that muscle atrophy and osteoporosis during space flights are related to the absence of gravity. Actually we have to consider another factor: instability. In fact postural and steering muscles need the interaction between gravity and instability to maintain adequate effectiveness and trophism [6]. Movements performed in terrestrial gravity, but without management of postural instability are ineffective in preventing muscle atrophy and osteoporosis. Muscular trophism is based on proprioception and interaction with gravity. As the muscles are also the steering organ of bone, bone will adapt to the reduced stress and strain placed on it by the muscles (Fig. 1). In terrestrial gravity the top priority of the system of movement control is “finding postural stability”, for all subjects (world sport champions, medium level athletes, astronauts, elderly people, motor impaired subjects). This law is valid regardless of the importance of the task you are consciously performing and it can be easily demonstrated without sophisticated experiments: just look at a person who is crossing a stream trying to gain a foothold on unstable stones. When his/her vertical stability becomes rough, every cognitive movement is continually interrupted to recover vertical control through postural compensation before resuming it. The aim of the antigravity control system is to manage instability in order to find stability [7] and minimize entropy. Entropy means “disorder” of a system and a universal law says that “the lower the entropy the higher the expressible energy”. In fact that condition is indispensable to keep the fluency of movements and perform refined motor skills. That is the reason why world and Olympic champions of terrestrial ground sports have a very low level of postural entropy, depending on very refined postural control (Fig. 2).

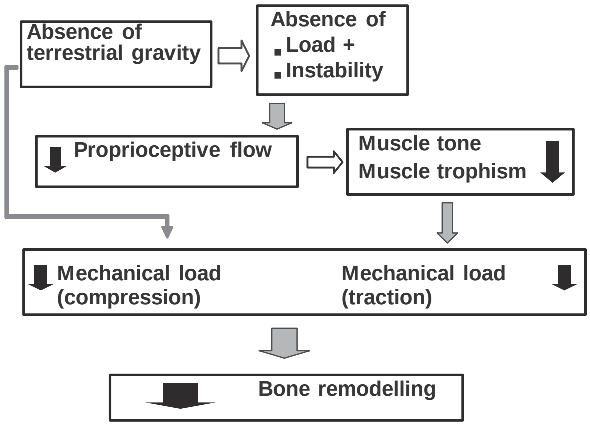

Fig. 1. Functional and structural consequences of the absence of load and instability on postural muscles and bearing bones.

Subjects training with strength machines (e.g.: leg press), which do not require instability management, have poor postural stability and, as a consequence, they are unable to use their increased strength because they cannot control it. All subjects with poor postural stability and consequent high entropy cannot express their full physical potential, because they compromise fluency and effectiveness of the antigravity activities (running, jumping, etc.) and of the additional technical movements. It is the quality and the frequency of the postural situations to be managed which optimize the trophism and refine the activity of the postural muscles. At the same time those situations apply compressive load and traction forces to the bearing bones, factors indispensable to their remodelling.

Proprioception [8] is the flow of signals arising from the receptors of muscles, tendons, joints and skin. It includes “conscious” and “unconscious” components.

Postural control and functional stability of the joints are based on the proprioceptive stabilising reflexes. To understand the importance of the unconscious component it is enough to bear in mind that among the signals that arise from muscles, joints and skin, approximately only one out of a million is able to reach the conscious level. The refined regulation of postural control and of all movements is managed at the unconscious level. The conscious component of proprioception includes the joint position sense and the joint movement sense (kinesthesia).

The flow of signals deriving from the peripheral mechanical, visual and vestibular receptors is integrated

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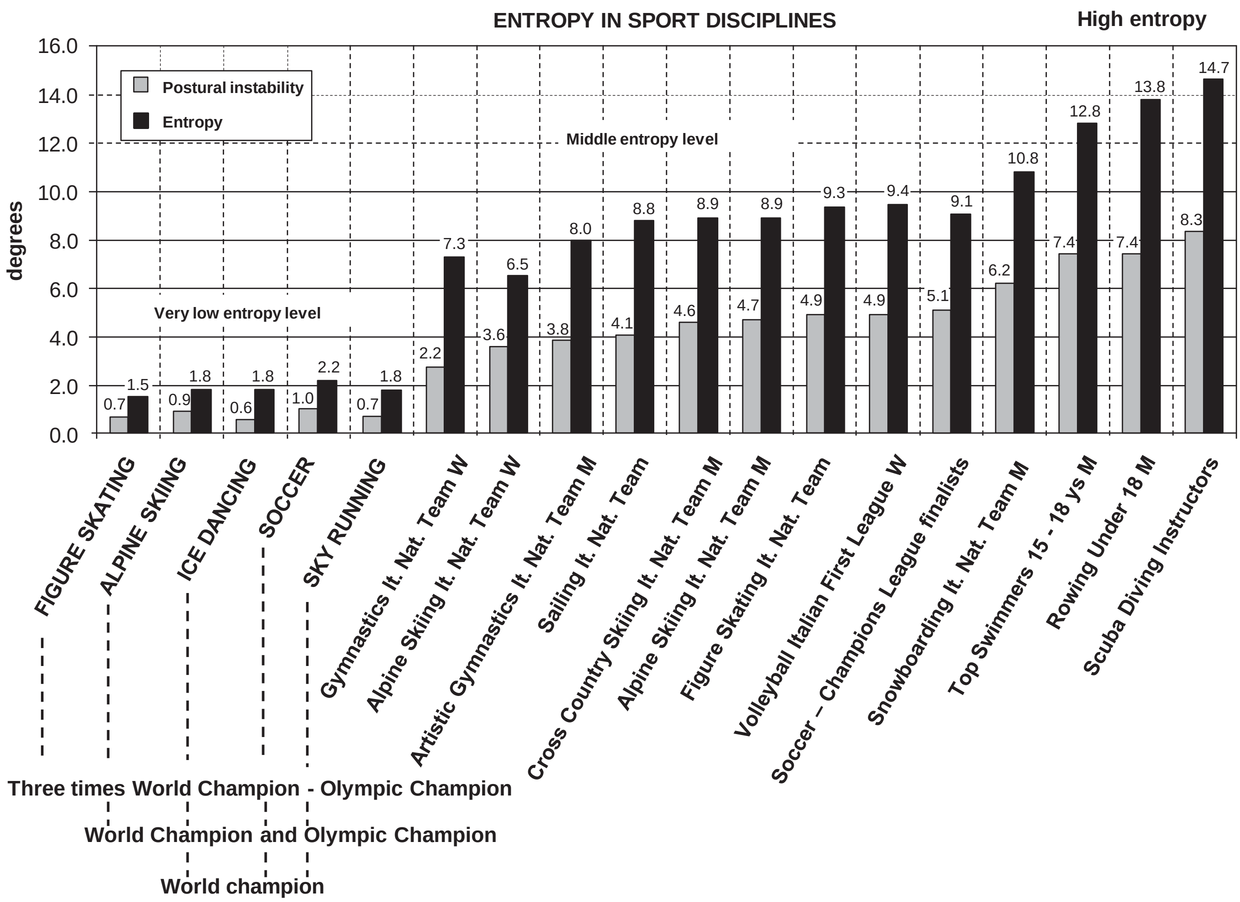

Fig. 2. Entropy in sport disciplines. The first five couples of columns on the left refer to single subjects, the other couples represent groups with at least 10 athletes each. Lower columns correspond to smaller entropy. The graph is based on the Dynamic Riva Test performed with Delos Postural Proprioceptive System.

and elaborated at various levels of the central nervous system.

The subcortical levels of this elaboration (spinal cord, brainstem and archeocerebellum) are the oldest zones of the nervous system and are common to the other vertebrates. It means that we have a powerful centre of control, but very often hypokinesis causes its functional worsening without anatomical damage. How can we maintain and recover its functionality?

Postural muscles are hungry for signals: instability and gravity feed them through proprioception. The reduction of motor experiences (hypokinesis) characterising the Western population can lead to a progressive proprioceptive and postural deficit with functional joint instabilities, impaired capacity of equilibrium and increased risk of fall. This situation is responsible for the choice of more and more simplified motor tasks and a further worsening of hypokinesis. A medium and long term structural consequence of this situation is accelerated negative bone remodelling.

3. Proprioceptive activation

In the last 15 years the development of a new assessment technology (Delos Postural Proprioceptive System—Delos s.r.l. Torino, Italy) has allowed us to measure the efficiency of the systems of equilibrium and postural control that are at the basis of the anti-gravity movements (walking, running, jumping,…).

This electronic system, composed of a rocking board (DEB) and a postural reader (Fig. 3) applied on the sternum (DVC), discovers in a few minutes the characteristics of the static and dynamic postural control of a subject and quantifies his postural strategies.

The rocking (rolling+inclination) of the board (Fig. 4), that at every instant is visualized through the

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Fig. 3. The postural reader is placed in sternal position before the parabolic flight.

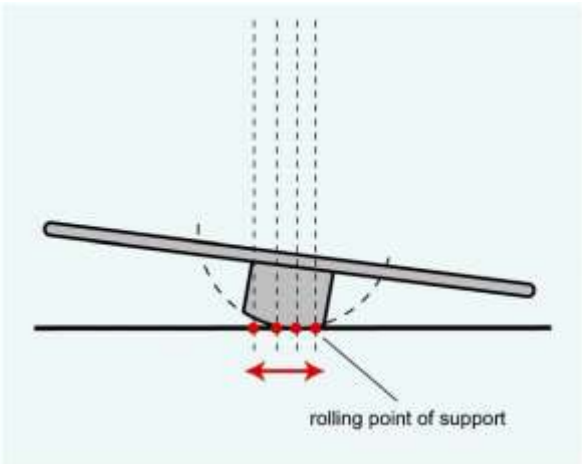

Fig. 4. The rolling of the board requires a continuous postural adaptation.

traces on the monitor, tracks (tracking: following of traces) the subject onto a new postural situation to manage [9]. The visual-tracking (it is a real-time feedback of the rolling and inclination of the board) notably increases the number of biomechanical situations that the subject in single stance has to manage in the time unit. On a Freeman board, without visual-tracking, you can manage rocking instability only at low frequencies. The management of rolling at HF generates a massive flow of signals directed towards the nervous system, which is trained to supply more and more refined and rapid replies. In this way the mechanical answers change

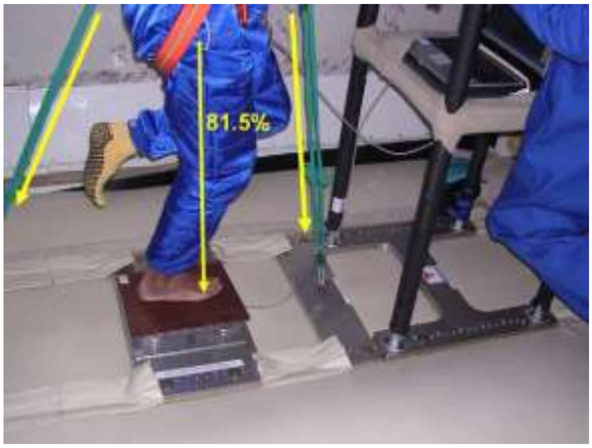

Fig. 5. The subject is on the electronic rocking board in microgravity conditions. The applied load was about 81.5% if compared to terrestrial gravity.

from macroamplitude at low frequency to microamplitude at HF. The effect is similar to a full immersion course with a mother tongue teacher on your capacity of speaking and understanding a foreign language. In a similar way a Formula One driver improves his performance only by training at high racing velocity. To run the same circuit with a utility car, would instead be useless because the number of situations that the pilot has to manage in each time unit is very low. To be effective the frequency must be specific.

Therefore, training the control systems of movement becomes a priority demand and to do this it is necessary to experiment situations of HF instability in order to generate a higher number of proprioceptive signals. In fact the inhibition of the proprioceptive flow inhibits muscular contraction [10].

The feasibility of HF visual proprioceptive training in a microgravity condition was demonstrated in Fort Lauderdale (Florida, USA) on 10th April 2005, during the "World's First non-governative Zero-G Science Campaign" carried out by Cosmo Spaceland Association and endorsed by Regione Piemonte (Italy). To obtain instability situations at HF it is necessary to track the subject, in single stance on a rocking platform, to real-time visual signals. The real-time visual signals (showing the rolling of the point of support) track the control systems of the subject, increasing the frequency of postural situations to be managed. In microgravity a bungee-cord loading apparatus (Fig. 5) allows the subject to manage, in this HF instability condition, the 100% body weight load. In this way the rising flow of proprioceptive signals activates the reflex contraction of postural and steering muscles, keeping their trophism

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Table 1
Suggested periodical assessments of postural stability, strategies and entropy.

(A) Pre-mission
(a) Pre-training
(b) Steady-state phase (reference value)
(B) During the mission
To monitor changes and adapt training sessions
(C) After the mission
(a)During recovery to optimize it (3 sessions/week for 3 months)
(b) Every 3 months after the recovery period (for 2 years)

at an adequate level for managing the situations usually faced.

The goals of that parabolic flight were to assess if:

- HF visual proprioceptive exercises can be performed in microgravity.
- It is possible to reach frequencies of biomechanical instability comparable to those reachable in terrestrial gravity.
- The action of the bungee-cord loading apparatus allows the subject to manage a load on the bearing bones comparable to that applied in terrestrial situation.

The results confirmed that:

- HF visual proprioceptive exercises can be performed in microgravity.
- Maximum frequencies of biomechanical instability reachable in microgravity are comparable to those reached on the Earth.
- During the parabolic flight in microgravity condition the applied load (indirect measure) was about 81.5% if compared to the same condition in terrestrial gravity (but can easily be increased).

The HF variations of load and strain applied to the skeletal structure represent a closer situation to terrestrial gravity conditions with respect to the other countermeasures currently used. Therefore, this methodology could be of great help to astronauts in avoiding muscular atrophy and postural control deprogramming.

Table 1 contains a proposal of periodical assessments of postural stability, strategies and entropy. Table 2 suggests a preliminary training programme schedule on the Earth and in space or on the moon. Most of the pre-mission training could be terrestrial with a part in an underwater environment and a very small part in parabolic flights to refine the procedure and to optimize working protocols in microgravity conditions.

The feasibility of proprioceptive underwater training has been tested and was shown on a television programme of the Italian Broadcasting Network (RAI—channel 3) in May 2005.

The aim of the pre-mission training should be:

- Optimizing postural and steering muscle trophism.
- Minimizing entropy.
- Improving capacity of managing high levels of HF micro–macro instability through visual-tracking.
- Minimizing training time.
- Performing strength exercises in single and double stance in instability and hyperload conditions (using the same apparatus for creating terrestrial load in microgravity) for the antigravity muscles of the lower limbs and of the trunk. The aim of these exercises is to train the phasic muscles under the driving control of the tonic muscles.

4. Comparison with pathological muscle atrophy

A neurological pathology, like multiple sclerosis (MS), causes a lack of outcoming and incoming signals to the muscles with consequences on the strength and trophism of the postural muscles similar to that of the astronauts after middle term space fights. Studying the effects of HF visual proprioceptive training on these subjects could improve our knowledge of the effectiveness of this countermeasure. Even if there is no typical MS, and everyone with MS has a different set of symptoms, subjects with MS generally show altered strategies in balancing and walking. Our preliminary postural assessments show that they have low proprioceptive levels and strongly depend on sight to counteract terrestrial gravity. Moreover, they are not able to activate vestibular strategies in emergency situations and use precautionary strategies instead. Postural reprogramming sessions with visual proprioceptive exercises, acting on their residual potential, have shown important improvements in antigravity activity (reduced need of walking aids and increased walking resistance) [11]. A HF visual proprioceptive exercise originates a massive flow of proprioceptive signals: even if nervous fibres are compromised and are not able to deliver all these signals they however allow an increased flow. In a similar way in microgravity conditions the application of a compressive load and a HF macro–micro instability generates an important flow of signals from the periphery.

Table 2
Duration of single proprioceptive training sessions.

Training characteristics	Unit	Earth Introductory phase	Earth pre-Steady-state mission	Space During the mission	Earth Post-mission
Single session duration	Min	45	30 ± 10	30 ± 10	40 ± 5
Weekly session number		3	4–5	4–5	3
Weekly training time	Min	135	135 ± 15	135 ± 15	120
Weekly working time	Min	67	> 95 ± 10	> 95 ± 10	> 84
Working time (density) (% of training time)	%	50	> 70	> 70	> 70
Minimum weekly training required	Min	105	120	120	105
Single stance	Min	25+25	> 35+35	> 35+35	> 31+31
Double stance	Min	17	> 25	> 25	> 22
Average rolling point inversions	m	11,000–17,000	15,500–24,000	15,500–24,000	13,800–21,300
Average rolling point total distance		115–186	163–264	163–264	144–233

Proposal of weekly proprioceptive training for astronauts on the Earth (pre- and post-mission) and during the mission in space or in lunar environment. The week is used as the reference period, but the training program is flexible and can be composed of microcycles of different duration (e.g.: 3-days-work-one-day-rest + 2-days-work-one-day-rest, etc.), according to the mission demands. The minimum training time is suggested. The longest period without HF proprioceptive activation should not last more than 2 days.

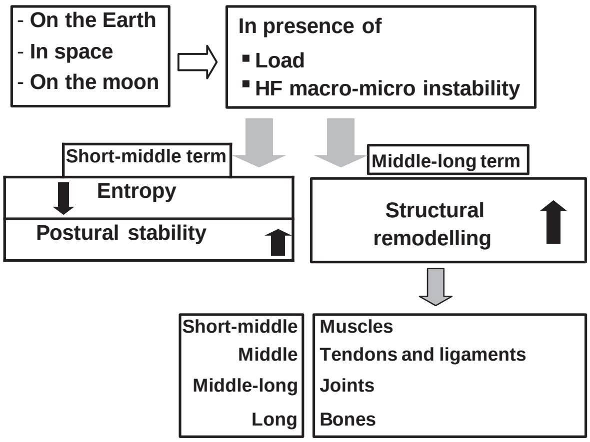

Fig. 6. Short, middle and long term functional and structural remodelling in presence of load and high frequency macro–micro instability.

5. Conclusions

In all environments the facing of HF postural instability is indispensable to generate active massive proprioceptive flows, not only for feeding muscle trophism but also for continuously reprogramming the functional level of the antigravity movements. The possibility of generating HF proprioceptive flows, even in conditions of hypogravity or zero-gravity, could complement current countermeasures for the prevention and recovery of muscle atrophy and osteoporosis in terrestrial and space environments. In fact, these exercises combine massive activation of spindles and joint receptors, applying simultaneously HF variations of pressure to different areas of the sole of the foot with the rolling support. HF proprioceptive activation is a method which can easily be applied in all environments, without risk. Thousands of tests and working sessions on the Earth with athletes and patients affected with different pathologies and the trials in microgravity permit us to hypothesize that this class of exercises could improve the effectiveness of present countermeasures, reducing working time and fatigue. At the same time these exercises apply mechanical load and hyperload (if compared to terrestrial situation) to the bearing bones, combining the compressive forces with the traction forces, generated by the reflex contractions of the postural muscles. In middle-long term these forces contribute to the structural remodelling of tendons, joints and bones (Fig. 6).

Conflict of interest

D. Riva (MD) is the Scientific Director of Delos and he holds company equity. The company and D. Riva hold the patent for the electronic rocking board. None of the other authors has any conflict of interest.

References

[1] I.B. Kozlovskaya, A.I. Grigoriev, Russian system of countermeasures on board of the International Space Station (ISS). The first results, Acta Astronaut. 55 (3–9) (2004) 233–237.
[2] I.B. Kozlovskaya, I.V. Sayenkoa, O.L. Vinogradovaa, T.F. Millera, D.R. Khusnutdinovaa, K.A. Melnika, E.N. Yarmanovaa, New approaches to countermeasures of the

negative effects of microgravity in long-term space flights, Acta Astronaut. 59 (1–5) (2006) 13–19.

[3] C.S. Layne, K.E. Forth, A.F. Abercromby, Spatial factors and muscle spindle input influence the generation of neuromuscular responses to stimulation of the human foot, Acta Astronaut. 56 (2005) 809–819.

[4] M.S.F. Clarke, C.S. Layne, D.A, Martinez, D.L. Feeback, A. Kyparos, Using dynamic foot pressure as a countermeasure to muscle atrophy, Institute for Space Systems Operations, 20–30, Annual Report 2004.

[5] D. Riva, P. Trevisson, R. Minoletti, M.C. Riccio, Sports influence on dynamic postural control during human growth, in: G. Gilli, L.M. Schell, L. Benso (Eds.), Human Growth from Conception to Maturity, vol. 34, Smith-Gordon Publisher, London, UK, 2002, pp. 325–332.

[6] C.S. Layne, A.P. Mulavara, P.V. McDonald, C.J. Pruett, I.B. Kozlovskaya, J.J. Bloomberg, Effect of long-duration spaceflight on postural control during self-generated perturbations, J. Appl. Physiol. 90 (2001) 997–1006.

[7] D. Riva, P. Trevisson, L'augmentation de la force exprimable pour l'optimisation de la performance sportive, vol. 445, KS—Kinésithérapie Scientifique, Paris, 2004 pp. 27–32.

[8] C.S. Sherrington, On the proprioceptive system, especially in its reflex aspects, Brain 29 (1906) 467–482.

[9] D. Riva, Archeopropriocezione, Sport Med. 2 (2000) 49–55.

[10] J.C. Kennedy, I.J. Alexander, K.C. Hayes, Nerve supply of the human knee and its functional importance, Am. J. Sports Med. 10 (1982) 329–335.

[11] D. Riva, A. Nebbiai. Postural strategies in multiple sclerosis: assessments, reprogramming and functional recovery, In: Fourth International Symposium on Complementary Supportive Therapies, Pola, Croatia, 2006.

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