# Musculoskeletal Model, Countermeasure and Bone Analysis for Astronauts

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## 1. Summary

The Anybody Modelling of Muscles and Bone Strain for Osteoporosis Research and Bone Loss in Microgravity Activity was a European Space Agency activity performed by Anybody Technology (2008).
The objective of this activity was to investigate and simulate the effects of microgravity on muscle behaviour and bone strain to support countermeasure development and to optimise hardware design and exercise prescription.

These objectives were realised through a two phased feasibility study:
- The strain acting on the bone (tibia) was simulated and analysed during one time point in 1g and 0g conditions during a treadmill walking cycle
- The muscle activity was analysed during a typical countermeasure exercise activity.

With the use of AnyBody software it was tried to gain a tool - or more specific an engineering approach - able to analyse the microgravity effects on muscles and bones and to optimise hardware and tasks used with astronauts.
This paper will show the background of the problem of bone loss in microgravity and will provide an overview of the first feasibility study to analyse the problem with the AnyBody modelling.

## 2. Keywords

Space technology, Microgravity, Anybody Modelling, Bone loss research, countermeasure device

## 1. Modelling of Muscles and Bone Strain for Countermeasure Development and Bone Loss Research in Microgravity

## 3. Background

### *3.1 Bone loss in Microgravity*

Bone loss in microgravity is a major problem for manned space flight, especially for extended stays in microgravity. The loss is estimated to be 1-2% every month especially on weight bearing bones (e.g. in [1] a density decrease of the proximal femur of app. 10% during a 6 month space flight is reported). The bone decrease is thereby showing a wide variety in intra and inter-individual data [5] - some astronauts are showing large tibial deterioration, others much less. Even intra-individually the loss is not uniform – e.g. for the same subject the bone loss in the tibia can vary.

### *3.2 Countermeasures in Space*

Countermeasures are means to counteract the microgravity induced effects on the human body (through exercising, special nutrition, medication or restraining systems).
Until now the most prescribed countermeasure against bone loss in space is exercising [2]. Different countermeasure devices are therefore already on board of the ISS [13] like for example a treadmill, a cycling ergometer, or a resistance exercise device [5] shown on Figure 1.

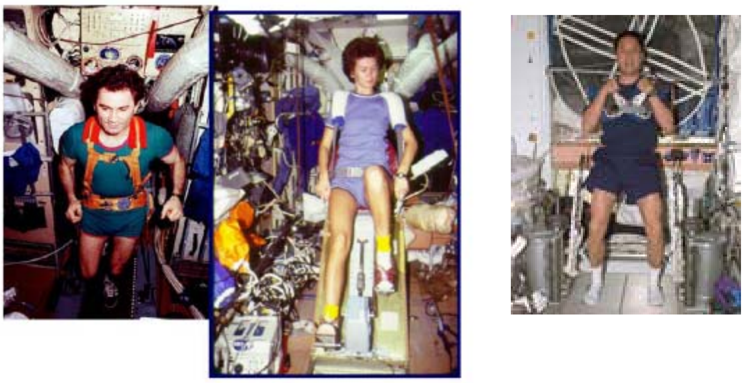

Figure 1: Countermeasure devices on board of ISS [4] / [13]

Performing daily exercises is a very time consuming activity for the astronauts requiring hours of the astronaut time every day. The achieved result however, is mostly only a decrease of the overall bone loss [4].

Currently new developments are aiming at more efficient countermeasure devices based e.g. on vibrating platforms [6]. One problem the countermeasure development is facing thereby is the limited availability of data acquired in space. New developments are for this reason based on an empiric approach: experience (including experience on earth) and trial (including bedrest studies). Bedrest studies are trials where subjects (divided into control and exercise groups) are resting with the head tilted down from 8 days up to 6 month, to simulate microgravity conditions [14].

### *3.3 Goal*

The goal of this activity was to see if it is feasible to analyse countermeasure devices or general tasks in microgravity with a modelling system based on reaction forces:
The most important goal was to see if muscle activation patterns can be transferred to a bone stress map. The goal was to analyse the differences between normal walking on a treadmill (at 1g) and walking on a treadmill in microgravity (for the walking in microgravity the body had to be strapped down by a modelled harness).

The general feasibility of modelling and the optimising of a countermeasure device was done on one example countermeasure device (a rowing ergometer developed by the ESE GmbH under European Space Agency contract- see Figure 2). The goal of this was to model the countermeasure device and analyse the muscle activation forces for a possible optimisation of the device.
Both parts have been implemented and analysed by the AnyBody group starting early 2008.

## 4. Tools and Methods

### *4.1 Anybody Modelling Software*

A very short description of the AnyBody modelling software can be given as follows:
The AnyBody Modelling System is a software system for the simulation of human movement. It can model smaller or larger subsets of the musculoskeletal system (or the entire body) and compute muscle forces, joint reactions, metabolism, mechanical work, efficiency, etc. for given movements. The Anybody whole body model comprises currently more than 910 independent activated muscles. To solve the problem of the muscle recruiting efficient optimisation algorithms are used as described in [4] and [6].

Figure 2 Anybody Human Musculoskeletal Model

### *4.2 New leg validation*

The prerequisite to start the analysis of the countermeasure and bone strain was the validation of a new detailed leg model, which was established as the first task of the presented activity. The new leg model consists of 159 individual muscles and allows for a very detailed analysis of the muscle activations which allowed the detailed determination of the strain leverage points for the second part of the activity.

### *4.3 Countermeasure rowing device*

To show the possibilities of optimising an already existing countermeasure device or a device in development, the next part of the activity was to model an existing countermeasure device. The rowing ergometer from ESE GmbH developed under ESA contract (see Figure 3) was chosen for this purpose.
Its Anybody representation (including the human model) can be seen in Figure 4.

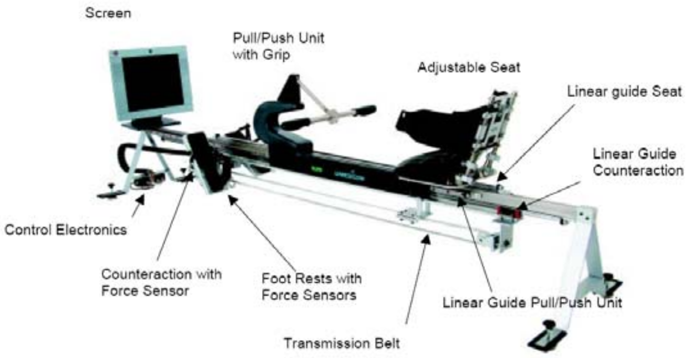


Figure 3 Endurance Trainer - example  countermeasure device

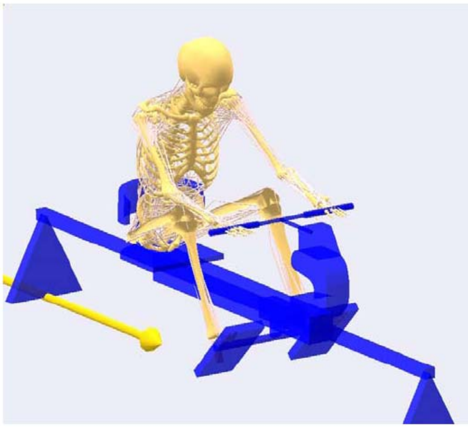

Figure 4 Endurance Trainer in the Anybody Simulation

### *4.4 Harness walking*

To make exercising in space possible astronauts have to use a harness system to get resistance either for walking on the treadmill or for any other kind of exercises – see Figure 1. Without a harness system every movement is inducing a countermovement in the weightlessness of space.

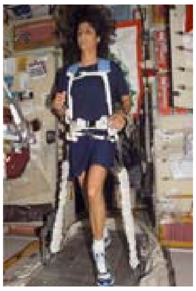

Figure 5 Treadmill walking on board of the ISS

Forces on the harness are thereby usually 80% or 100% of the bodyweight of the astronaut [3]. Typically the harness is designed to load the weight either only on the shoulder or on the shoulder and the waist of the astronaut. The latter gives a more equal distribution of the load and is more comfortable. The design chosen for this activity is the shoulder and waist harness design as it can be seen in Figure 5. The final AnyBody realisation is shown in Figure 6.

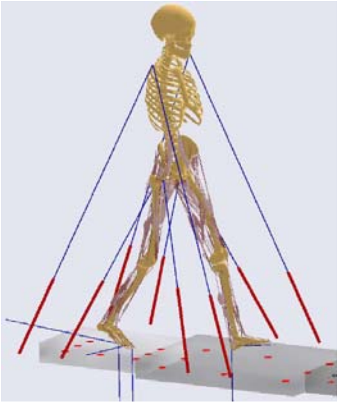

Figure 6 Realising of harness walking in AnyBody

*4.5 Bone strain analysis*

The main part of the activity was to analyse the bone load during normal walking on a treadmill and to compare it to the bone load while walking on a treadmill in microgravity (using a harness device).
As this activity is only a small feasibility study the analysis was limited to one bone and one time stamp during the gait. The tibia was chosen as example bone and, as time step for the comparison, the pre-swing (within the stance phase) was chosen.
A full Finite Element Model (comprising 183622 solid elements with quadratic shape functions) from the tibia was used to perform the analysis. All acting forces (originating from ground contact, bones and muscles) were transferred in the tibia to have a complete "map" of all resulting strains.

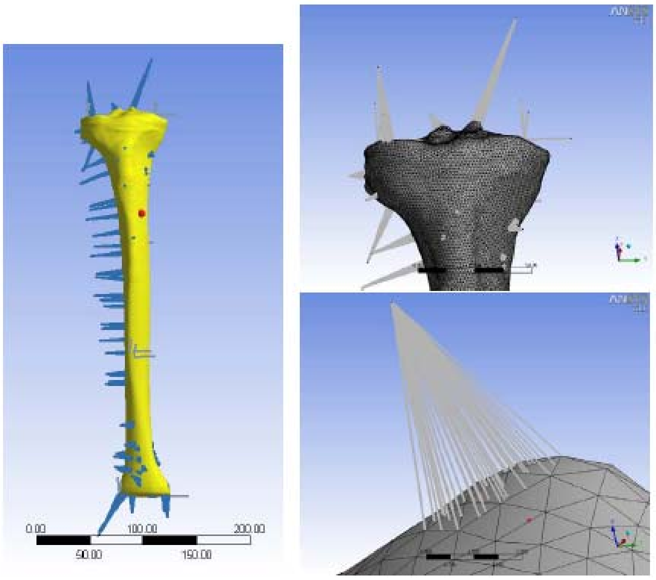


Figure 7 transfer of forces into the tibia

In Figure 7 it can be seen where the forces acting on the tibia are located (some muscles are modelled as a poly-line). Muscle via-points are represented with points located above the surface. Forces acting on the fibula are transferred with the blue bars to the tibia (the fibula itself is not modelled).

## 5. Results

*5.1 New leg validation*

The new leg model was used with the Anybody modelling software for the validation (the basic data for the new leg model was recently published [7]). For the validation the muscle activation was compared to literature including muscle moment arm lengths for the subtalar joint, ankle joint, knee joint, hip joint and isometric joint moments. Results show a good agreement of the AnyBody simulated muscle activations with actual muscle data taken from literature [8]. A preliminary overall performance analysis has been performed by comparing a test person using motion capturing techniques with the scaled AnyBody model. More extensive comparisons need to be carried out in order to validate the leg, but the preliminary results show a good agreement between real and simulated data.

### *5.2 General countermeasure simulation (rowing ergometer simulation)*

When the muscle activation results for the initial rowing ergometer countermeasure simulation during pull and push phase are compared a clear unbalance between both phases can be seen:
The modelled system was using 400N for the pull phase and 80N for the push phase (see blue line – partly covered by the red – in Figure 8). The analysis showed a too unbalanced difference between the pull and push force. To optimise this, a second simulation was performed – with push phase force set to 180N. Muscle activity for this second simulation shows a more balanced activation pattern (see red line in Figure 8) and the real countermeasure device was immediately adapted to the parameters of the second simulation.
A detailed analysis and optimisation should follow in a next step of the activity – running a complete optimisation loop to find the best suited parameters for optimal performance.

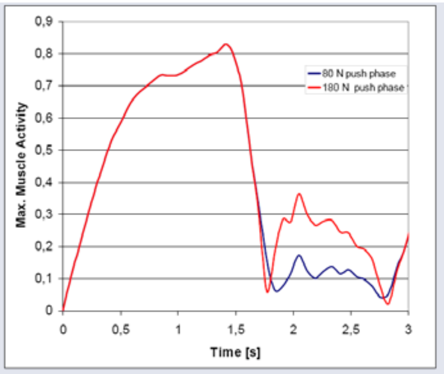


Figure 8 Anybody Muscle Activation for Countermeasure device

### *5.3 Harness walking*

The results of both treadmill walking simulations can be seen in Figure 9 and Figure 10. Figure 9 shows the resulting hip reaction forces of the normal treadmill walking at 1g while Figure 10 is showing the same walking pattern but with the forces originating from the harness instead of gravity (harness induced treadmill walking under 0g condition).

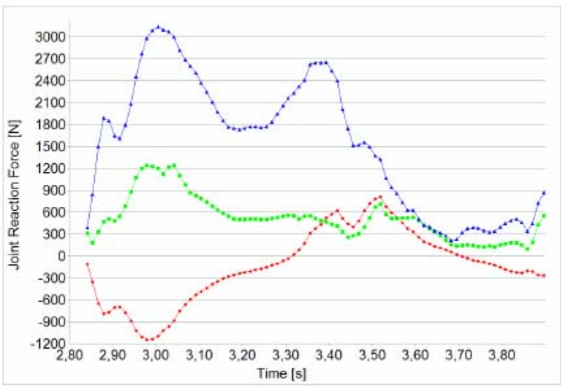


Figure 9 Hip Reaction Forces during normal 1g walking. The different curves refer to the force components in the global coordinate system: inferior-superior (blue), anterior-posterior (red) and medial-lateral (green).

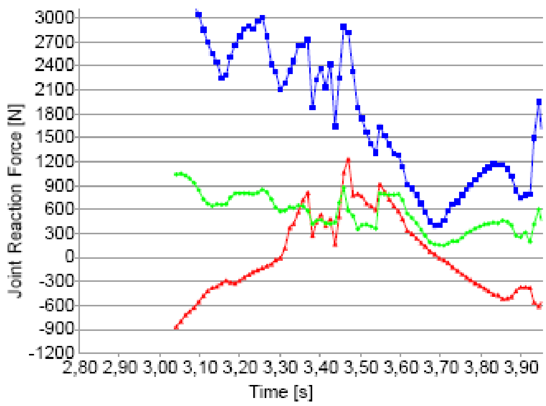


Figure 10 Hip Reaction Forces during 100%Body Weight (BW) 0g walking

As the presented activity is only a feasibility study and not a scientific evaluation, no scientific conclusion can be drawn yet from the present data. However, it is clear that differences between the joint reaction forces are apparent despite the fact that both gaits show approximately the same ground reaction force (shown in Figure 11):

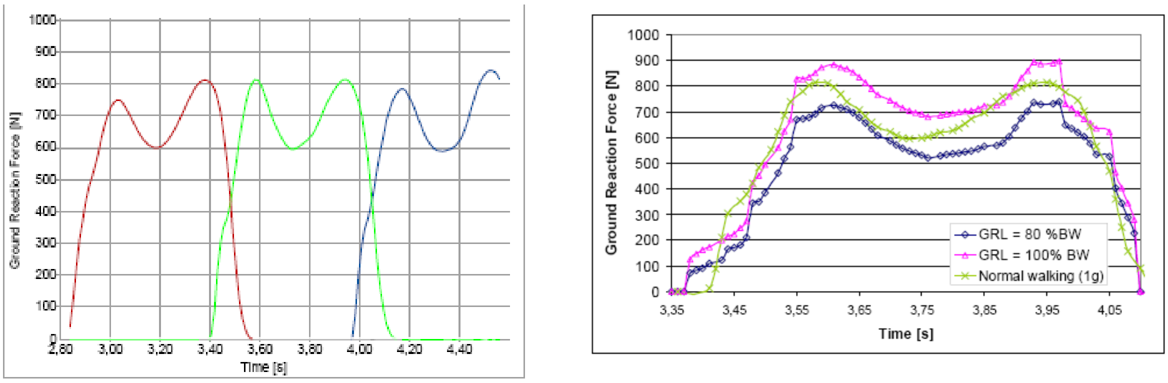


Figure 11 Ground reaction forces: on the left from 1g walking (red: right foot contact, green: left foot contact, blue right foot contact) and on the right the harness induced 0g walking (one foot contact shown only). The GRL indicates the percentage of body weight used.

### *5.4 Bone strain analysis*

Also the analysis of the bone strain during normal walking (1g) and under microgravity (with a harness providing the force to strap down the subject) shows clear differences as can be seen in Figure 12:

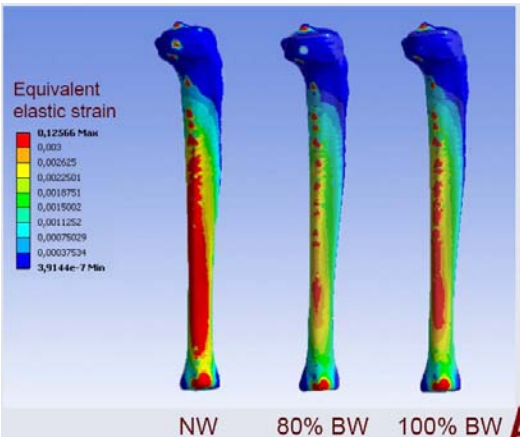


Figure 12 result of bone strain analysis. NW is representing 1g condition, 80% and 100% BW are representing 0g conditions with the harness (80% and 100% of the body weight)

The analysis was performed during one time step in the pre-swing gait phase. For harness induced walking a harness load of 80% and 100 % was simulated and compared to the normal treadmill walking.

Again, this is a feasibility study, no conclusion should be drawn for the strain analysis. But these preliminary results already show major differences between the bone loading in 1g and 0g. This could be an explanation of the fact that astronauts are loosing bone despite their performance of all prescribed exercises. However, all time steps have to be analysed to completely judge the bone loading as the harness may shift introduced forces to different peaks during the gait.

## 6. Summary and Outlook

### *6.1 Summary*

The European Space Agency funded activity *"Modelling of Muscles and Bone Strain for Osteoporosis Research and Bone Loss in Microgravity"* performed by AnyBody Technology, was investigating if a simulation based on a reaction force could be used to optimise devices for space as well as tasks performed in space or in general to support 0g experiments.
To achieve this, a new more detailed leg model was validated and with the use of the detailed leg an example countermeasure device was modelled and its parameters optimised.
In addition it was investigated if bone strain could be modelled based on the forces acting at the bone and if differences between 0g and 1g would be evidenced. A treadmill walking was used for the analysis: normal 1g walking and 0g harness walking were modelled and bone strain was calculated (using a Finite Element Model) during one time step of the gait cycle. For this all forces acting on the tibia were calculated and transferred into the bone with appropriate means. First results show differences between both types of walking even if the ground reaction force is to be considered as almost equal or even slightly higher for harness induced walking. Both parts of the activity show very promising perspectives to start a more extensive modelling.

### *6.2 Future work*

This feasibility study showed very promising results on both parts of the activity, but to be able to fully assess and use the system to optimise countermeasure or general tasks in space a more detailed modelling of the exercise activity should be started. The validation shall then include real data if possible captured on board the ISS. This dataset should be used to optimise all parameters for the (countermeasure) device and define necessary improvements on the hardware.
To go from the step of the feasibility study for the bone strain analysis in space to a complete simulation for accurate bone loss in space different points have to be addressed in future work:

- The model has to be detailed in terms of bone density and number of bones modelled.
- The system should be extended to simulate dynamic attributes like muscle fatigue.
- Real countermeasure data on earth and in space should be collected and compared with simulated data.
- Also the application at bedrest studies should be used to compare data between real control and exercise groups and simulated and real data.
- Another also promising analysis could be the analysis of frequencies at the bone strain on earth and in space to investigate the correlation between strain frequency and bone loss.

### *6.3 Parabolic flight*

To have a real basis for the validation and simulation work a parabolic flight should be emphasised. Here first of all the 0g-posture could be found and defined. It is expected that the posture under microgravity conditions will be the most relaxed position for muscles possible and will give a calibration for the muscle models.
During such an opportunity 0g data could be gathered - e.g. treadmill walking forces and patterns. This would provide data about the change of the actual walking pattern under microgravity conditions and could pave the way for a real engineering approach to countermeasure development, task optimisation and 0g effect simulation in space.

### *6.4 ISS on board facility*

The final challenge for the simulation and model verification would be a motion capturing experiment on board of the International Space Station to get real microgravity patterns and force data (after the adaptation of the astronaut to space and without interuptions of high-g phases as during the parabolic flights).

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