Subject Loading System (SLS) for the 2nd Generation Treadmill (T2) on the ISS

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Background and purpose

Microgravity is known to cause loss of bone and muscle mass. Current evidences indicate that impact loading, bone stress and muscular work, as implied by exercises such as treadmill running, are important countermeasures for maintaining bone and muscular mass. In microgravity, such an exercise requires a Subject Loading System (SLS) in space, *i.e.* a means to hold the subject down onto the surface of a treadmill while he/she runs.

Functional requirements

Established by the ISS International Partners (CSA, ESA, JAXA, NASA and RSA):

- Subject size: 5th % Japanese ♀ – 95th % American ♂.
- Static load range: 178 – 979 N.
- Load adjusted in 22.3 N steps.
- Static load accuracy: ±5 %
- Dynamic load accuracy: ±15 %
- Total dynamic load accuracy ±20 % (left plus right).
- Load rate: 89.2 – 133.5 N/s (initialization).
- Load rate: 22.3 – 44.5 N/s (stage transition/session end).
- Vertical displacement: ±10.2 cm.
- Pull-down cords origin: < 55 cm apart, within ±2.5 cm of the fore-aft centerline of the tread surface, within ±5.1 cm of the running surface plane.
- Subject displacements: over the entire tread surface.
- Attach/detach: < 2 minutes.
- Emergency egress: < 30 s.
- Tension measured at ≥250 Hz and stored periodically.
- Engineering data measured every 10 s and stored > 2 weeks.
- Operating lifetime of 10 years.
- Maintenance/repair specifications based upon 4 subjects running 1 h/day and 4 days/week.
- Annual on-orbit maintenance: < 12 h for a 3-person crew.
- T2 system noise < 65 dBA at a distance of 60 cm.

Design

<u>Studied concepts</u>: Over 15 candidate concepts, including different actuators (EMA's, springs, pistons, bellows) and transmission systems (cams, gear-boxes, fusees).

<u>Concepts rating</u>: against 15 trade-off criteria such as expected performance and accuracy, proof of concept, engineering budgets (mass, power, dimensions), safety, reliability, maintainability.

<u>Retained concept</u>: pneumatic pressure system (Fig.1)

- Cable pulling the subject down from each side.
- Low pressure, buffered, cylinder pre-tensioning cable.
- High pressure buffer refilling both low pressure buffers.
- Compressor refilling the high pressure buffer.
- Total of 5 valves controlling the flow of air.
- Sensors: 3 pressures, 2 pull-down forces, 2 positions.

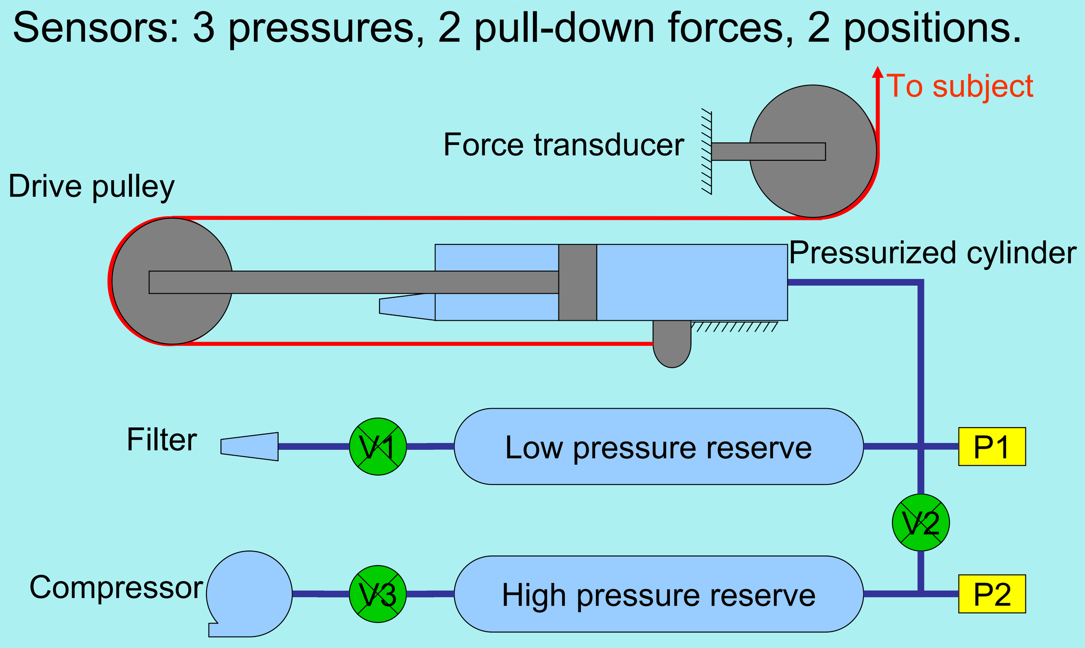


Figure 1. Conceptual design of the T2 SLS (one side only).

Prototype

The T2 SLS prototype is currently mounted in a simple test rack (*Fig. 2*) that allows the SLS to be driven with approximately sine wave displacements ranging in amplitude from ±5.0 cm to ±12.5 cm in 2.5 cm increments. The 'step frequency' can be varied from 0.1 Hz to 3 Hz. The pull-down force can be varied continuously between 0 and more than 500 N.

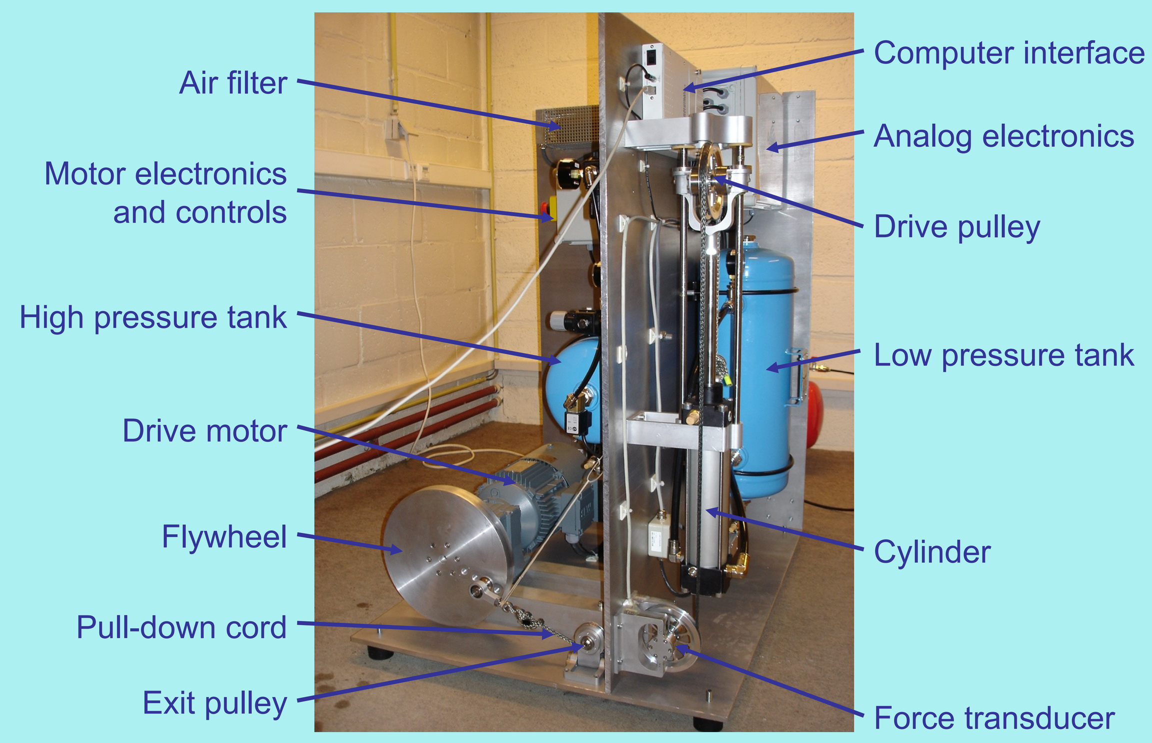


Figure 2. The SLSv2 test rack.

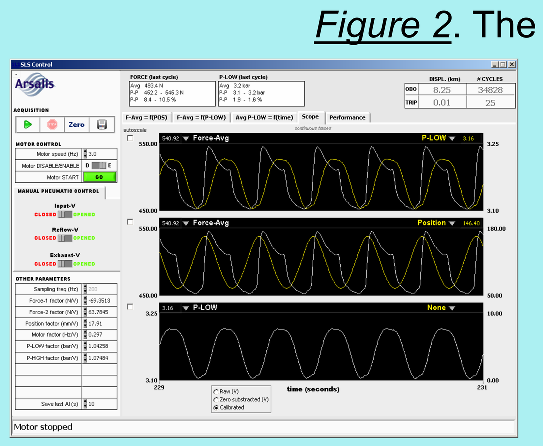


Figure 3. Plots of the pull-down force, low pressure and piston position versus time.

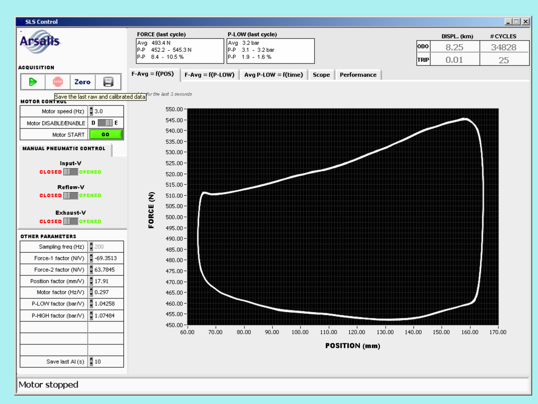


Figure 4. Plot of the pull-down force as a function of the piston position.

<u>Functional performance</u> tested in 120 conditions covering the range of functional requirements (*Fig. 5*)

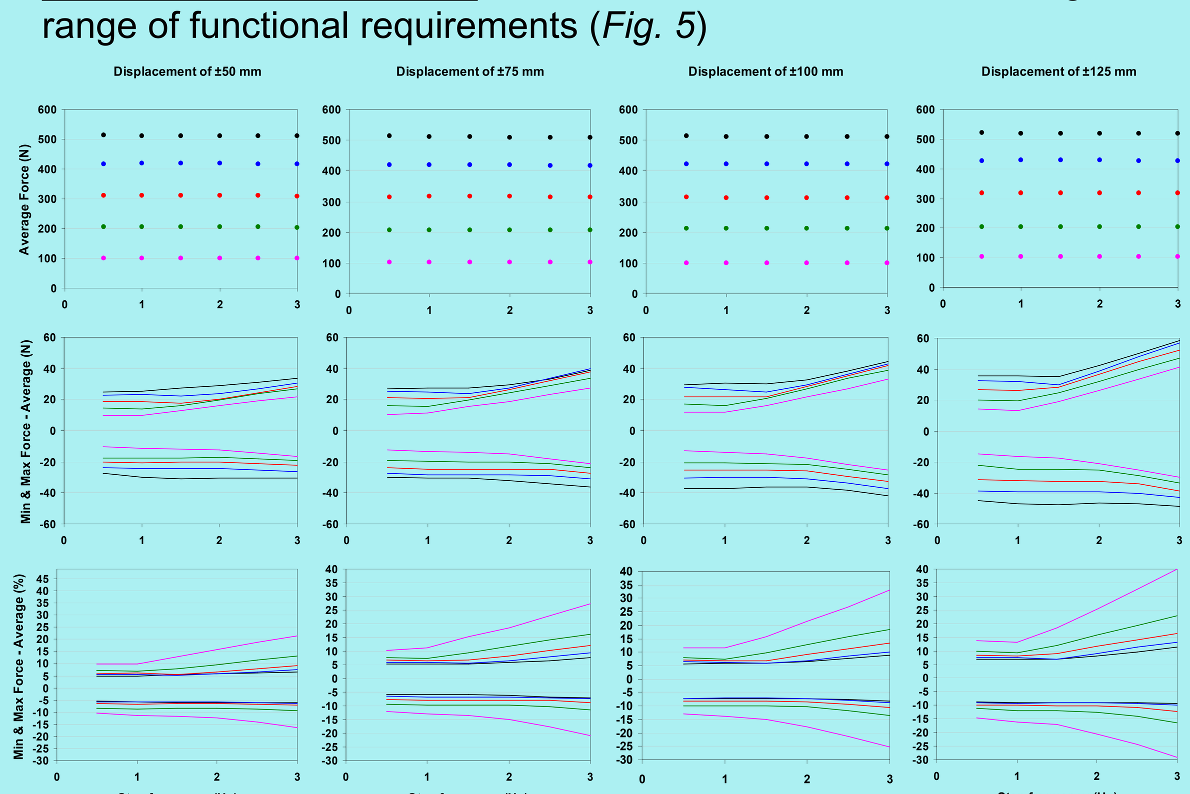


Figure 5. Dynamic load accuracy of the T2 SLS prototype when tested over 3 steps (cycles) at an average static load of 90 to 490 N (in 5 increments) and over a subject's vertical displacement of ±50 mm to ±125 (in 4 increments) mm as a function of step frequency.

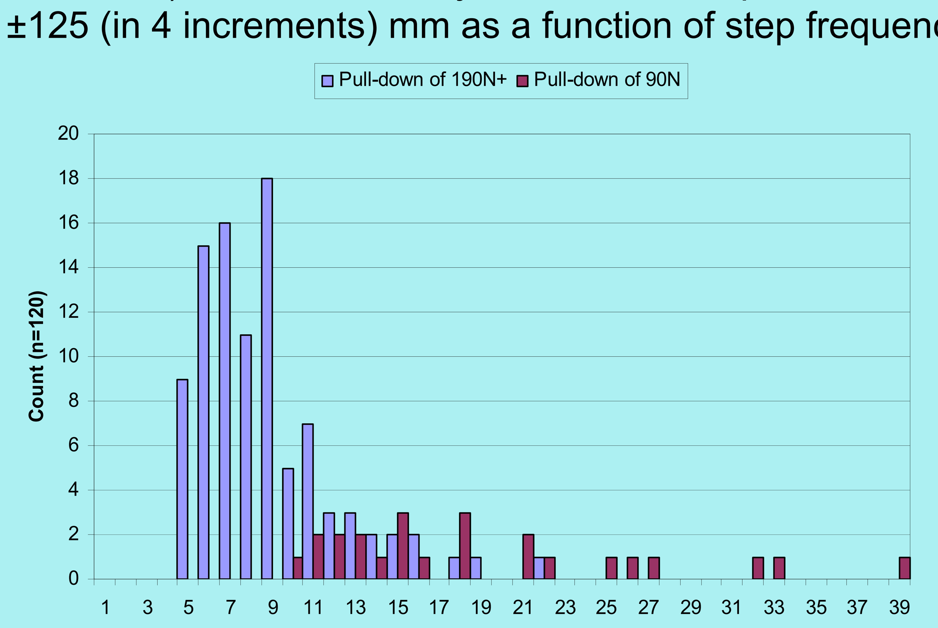
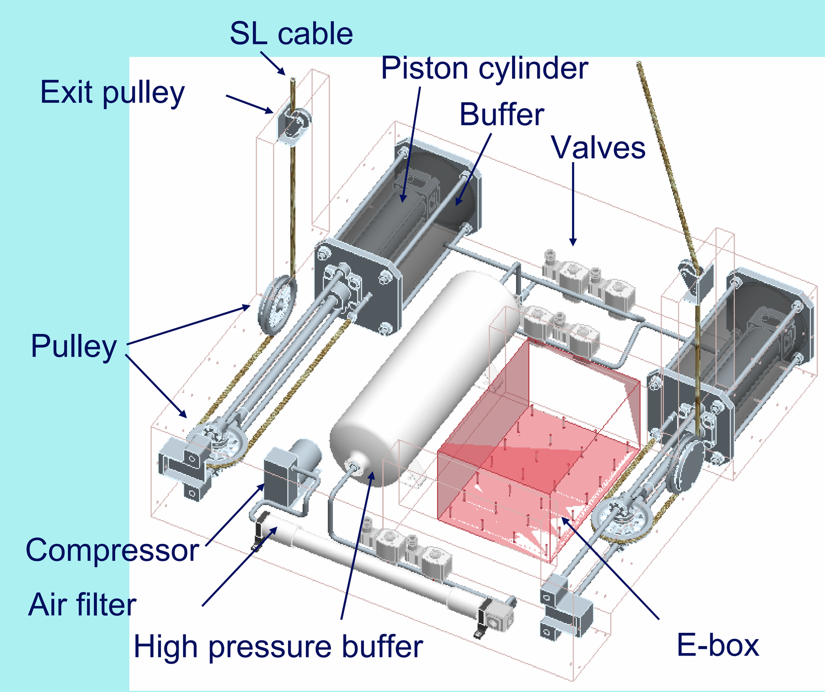


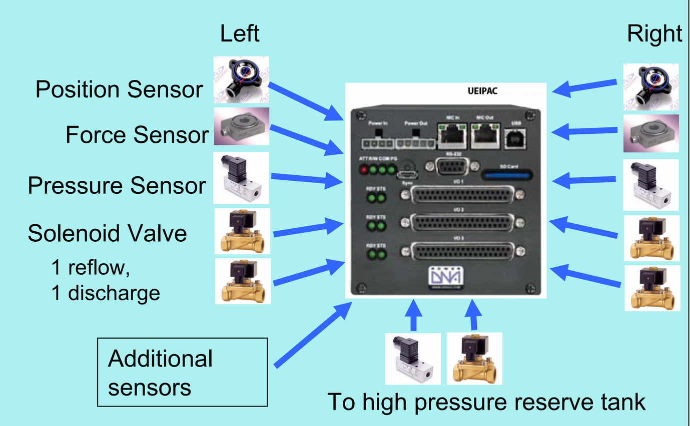
Figure 6. Distribution of the peak dynamic load deviation from the average pull-down force across the 120 conditions tested. **Overall, the dynamic load remains within ±15 % of the average load for 95% of the realistic conditions.**

Accommodation

The proposed concept fits the allocated volume within the T2 ISPR rack as shown in figure below.



The E-box contains a **UEIPAC** handling all physiological and engineering data of the SLS and controlling all SLS processes.



<u>Operations</u> determined with a 4 l buffer for each side and with a 9 l high pressure buffer shared between both side:

- <u>Changing pull-down force from 89N to 489N per side</u> Compressor activity required only to refill high pressure reserve and time required is only limited by maximum loading rate.
- <u>Changing pull-down force from 0N to 489N per side</u> Available time ranges from 7 to 11 s and required pumping time ranges from 0 to 10 s.
- <u>Refilling high pressure reserve tank to 6.85 bar</u> requires pumping time of 3min 52s.

Reliability and lifetime test

Lifetime operation of the SLS takes into account 4 subjects using the SLS 1 h/day for 4 days/week and 52 weeks/year during 10 years, including 10 min 'warm up' and 4 load/unload cycles per session.

Part	Lifetime	Rated life	FOS (TBC)	Margin of safety
Bearings	8,320 h	> 180,000 h	1.259	>17.2
Piston seal	18,000 km	3,000-5,000km	1.259	0.13 – 0.22, *i.e.* annual replacement.
Solenoid valves	0.5M cycles	> 10 M cycles	1.259	>15.9
Technora cable	No lifetime rating available. Specially designed to run around pulleys and has a breaking strength of 37.7 kN, and it will be used with a load not exceeding 500 N (*i.e.* with a safety margin of at least 75).			

Table 1. Reliability of all wearing parts of the T2 SLS.

Total number of cycles were fitted to a normal distribution of loads over the range of subject's sizes, allowing one year of operation to be simulated in 35 days.

<u>SLS Lifetime Test Plan Summary</u>

- Subject weight (kg @ 1*g*): 40.8 to 100
- 1*g* pull-down force/2 (N): 200 to 490
- Subject step frequency (Hz): 2 to 3
- SLS stroke length (cm): ±5, ±7.5, ±10
- Min (unloaded) pull-down (N): 89
- 'Running' tests (cycles): 10.68M
- 'Loading' tests (cycles): 9,115

Functional analysis

A functional analysis showed that:

- The theory fits with the measured performance
- Minimal improvements can increase performance (*Fig. 7*)

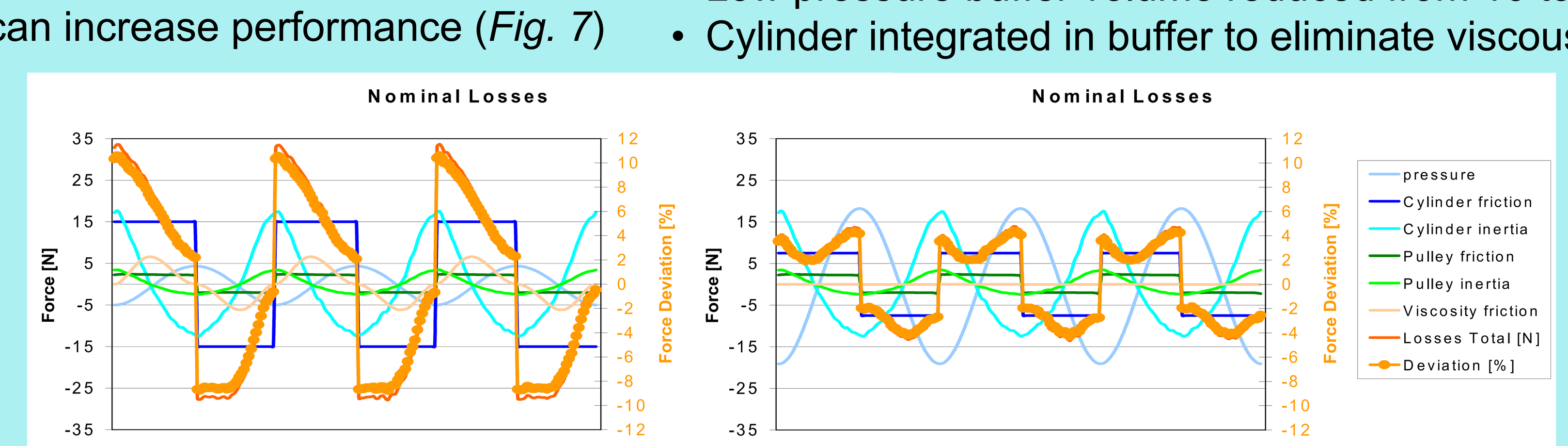
<u>Simulated improvements</u>

- Reduced friction and inertia,
- Low pressure buffer volume reduced from 16 to 4 liters,
- Cylinder integrated in buffer to eliminate viscous losses.

Figure 7. Nominal losses due to various components.

Conditions:

- stroke = 75mm;
- preload = 290N;
- frequency = 3Hz.



Conclusions

- The "pressurized piston" is the highest rated concept and can easily be accommodated inside the T2 ISPR rack.
- The current prototype already meets or exceeds all performance requirements with minor exceptions than can easily be resolved.
- The test rack can simulate one year of operation in 35 days (accelerated lifetime test).
- Currently, no critical technical issues are identified which could prevent the achievement of a future flight model. Safety and reliability issues will however require continuous focus during all future project phases.