Validation of Musculoskeletal Contact Force Predictions in Supine and Semi-Supine Postures Using Pressure Mapping

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***Abstract* - This study presents a validation of musculoskeletal contact force predictions in supine and semi-supine postures using pressure mapping data. Two healthy individuals were assessed on a mock-up surface while force distribution along the back was recorded. These experimental results were compared with simulations from the AnyBody Modelling System. A grid convergence study was performed to optimize contact node placement, and key model parameters were tuned for best fit. The simulation showed good agreement with measured data, with an average error of 13.9%. This validation establishes confidence in using musculoskeletal models for future ergonomic and biomechanical posture analysis**

Keywords - Pressure Mapping, Musculoskeletal, AnyBody, Supine, Sacrum, Human Spaceflight, Validation

I. Introduction

Human spaceflight presents a challenge to astronaut safety and health, particularly in the high-acceleration phases of launch and return to Earth. Improving astronaut posture is not only important for comfort but also for reducing the risk of musculoskeletal injury and mission success [1]. Of the range of postures assumed in crewed spacecraft, the supine and semi-supine are especially significant in countering the impacts of elevated gravitational forces (i.e. G-forces) on the human body [2]. These postures are intended to transfer loads more evenly and minimize areas of localized pressure points, thus safeguarding space travellers against discomfort and possible harm [3].

There is a need to model and analyse the interaction of the human body with its surroundings when subjected to different types of load. Computational software facilitates musculoskeletal modelling, enabling simulation of intricate interactions between the body and support surfaces. One such software is the AnyBody Modelling System (AMS), which can be used to predict the forces and pressure experienced by astronauts while adopting different postures [4].

In particular, the contact force model in AMS needs to mimic accurately the true pressures that the human body faces while in static postures. Pressure mapping technology offers a non-invasive and accurate means of measuring these contact pressures in real time. Comparing the AMS simulation results with the pressure mapping data permits to test the model validity and adjust its parameters in order to better fit the data.

This paper describes a validation study that contrasts the contact force predictions of the AnyBody Modelling System with experimental pressure mapping results for supine and semi-supine postures. The main aim of this research is to confirm that AMS can accurately simulate the contact forces imposed on astronauts in these life-critical positions, thus facilitating continued development of more comfortable and safer spacecraft seating systems.

II. Literature Survey

Pressure mapping technology provides a non-invasive measurements of force distribution, which has been extensively used in clinical settings to reduce pressure ulcer risk and improve comfort in wheelchairs and mattresses [5]. Coupled with musculoskeletal models such as the AMS, which simulate internal forces and joint loading, these empirical data enable accurate prediction and analysis of biomechanical stresses on the back [4][6]. Validation of these models facilitates their application in ergonomic design and posture analysis is well described in [7].

In the context of human spaceflight, understanding back pressure distribution takes on heightened importance due to the unique challenges posed by microgravity, which alters normal spinal loading and can lead to back pain and musculoskeletal deconditioning [8]. Accurate pressure mapping in supine and semi-supine postures supports the design of spacecraft seats and seating arrangements that mitigate these risks by providing appropriate support and reducing discomfort.

Recent work at [9] [10] highlights the use of AnyBody in simulating ergonomic seat postures and validating musculoskeletal loading under various interface conditions. These studies demonstrate the growing relevance of combining simulation with experimental methods in biomechanics. However, relatively few studies have validated such simulations specifically for supine or semi-supine postures, particularly under space-relevant analogs.

This underscores the significance of the present study in addressing a critical gap in human spaceflight ergonomics.

Validated musculoskeletal models informed by such data are essential for developing effective countermeasures to maintain astronaut health during prolonged missions, ensuring that ergonomic solutions are both scientifically grounded and practically effective in the unique environment of space [6]. Thereby, validating the data obtained from pressure mapping source is essential for identifying hotspots causing discomfort to the human and mitigate it for further studies.

III. Methodology

A. Experimental Procedure

Two healthy adult participants were recruited for this study. Participant anthropometric data are presented in Table 1. Both subjects were male, aged 22 and 23, with healthy BMI and no history of spinal or musculoskeletal disorders. Procedures were performed with informed consent from both subjects.

Table 1. Subject Anthropometric Details

Subject	Age (in yrs.)	Height (in cm)	Weight (in kg)
S1	23	174	72
S2	22	173	67

Each subject was positioned sequentially in both supine and semi-supine postures on a custom-designed mock-up surface (Fig. 1 and Fig. 2), which was constructed to closely replicate the geometry and support conditions of a typical crew seat environment encountered in human spaceflight.

Two high-resolution XSensor LX100:40.40.02 and LX100:36.36.02 pressure mapping mats were placed directly beneath each subject's back to record the interface pressure distribution. The pressure mapping system was having a sampling frequency of 39-45 frames/s with a spatial resolution of 12.7 mm and pressure range of 0 - 34.13 kPa.

For the supine posture, the mat extended from the head to the sacrum (Fig. 1), ensuring comprehensive coverage of the contact region. In the semi-supine configuration, subjects

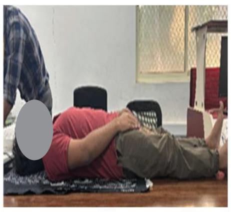


Fig. 1. Subject in supine posture

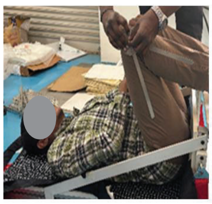


Fig. 2. Subject in semi-

were positioned on a mock-up crew seat with the pressure mat similarly aligned to capture relevant back contact areas (Fig.

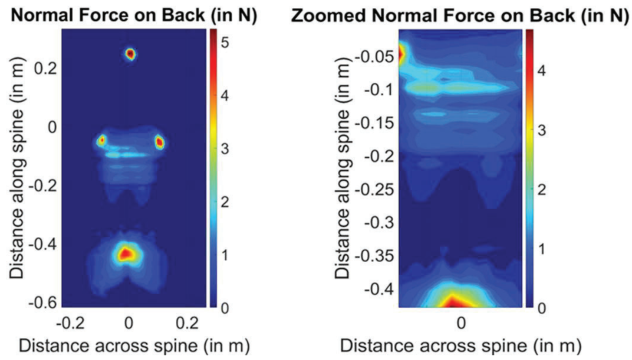


Fig. 3. Experimental Normal force contour and (Zoomed image) Force contour on back using pressure mapping for Subject 1 in supine posture

2). Each posture was maintained for a minimum of two

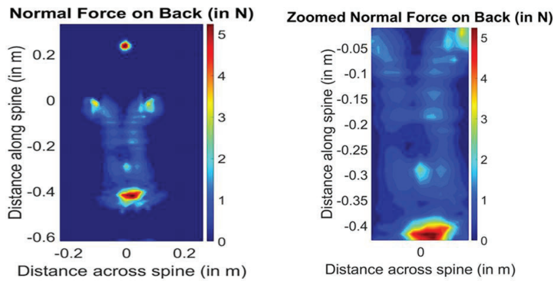
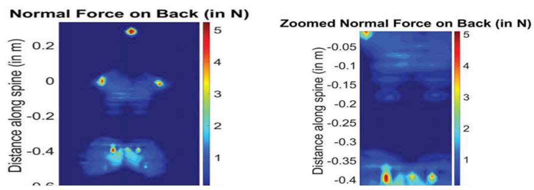


Fig. 4. Experimental Normal force contour and (Zoomed image) Force contour on back using pressure mapping for Subject 2 in supine posture

minutes to allow pressure stabilization before data acquisition



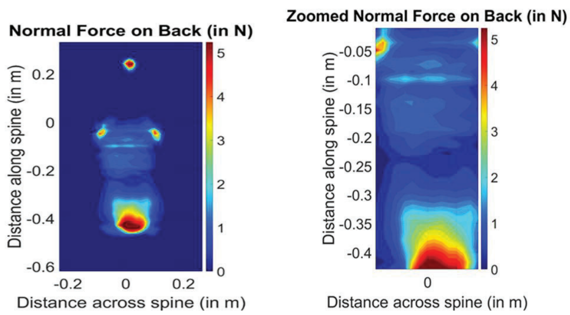


Fig. 6. Experimental Normal force contour and (Zoomed image) Force contour on back using pressure mapping for Subject 2 in semi-supine posture

and exported in a (.csv) format.

The raw pressure data were imported into MATLAB for post-processing. Initial force contour plots were generated to visualize the full head-to-sacrum pressure distribution for each subject in the supine posture as seen in Fig. 3 and Fig. 4. These contours were then refined by zooming into the back region, corresponding to the anatomical locations of interest and aligning with the contact node arrangement used in the AnyBody Modeling System (AMS) for direct model validation. The same procedure was repeated for the subjects in the semi-supine posture as visualized in Fig. 5 and Fig. 6.

For quantitative comparison with AMS simulations, the average force values recorded by the pressure mapping system were extracted for each posture and subject. As the current AMS contact models do not account for lateral (left-right) variation in pressure distribution, only the normal force values were considered in the comparison. This approach facilitated direct evaluation of the model’s accuracy against empirical measurements.

B. *Assumptions*

The assumptions presumed for the simulations are listed below:

- AMS muscles applies only to the European population; Indian population differences are not considered.
- Subject-specific strength scaling was not considered
- Spine curvature is ignored; contact nodes assume a straight profile, leading to uniform medial-lateral contact
- Soft-tissue deformation is not modeled, possibly underestimating contact area.
- Material properties of seat padding and human tissues (skin, fat, muscle) are not included in AMS
- Simulations performed under static conditions; dynamic loading from High-G phases is not yet captured

C. *AMS Modelling Setup*

A complete human musculoskeletal model was obtained from the AnyBody Muscle Model Repository (AMMR) in AMS, as shown in Figure 7, which represents the Caucasian population [11]. The anthropometry data (height and weight) from Table 1 and simple muscle model were used. Finally, the length-mass-fat scaling law was used to scale the skeletal structures. The lower extremity model is based on the TLEMsafe 2.0 data set [12].

Two such models were developed; one was a human supine model and the other was a human sitting on a seat model in semi supine posture. This was done, to understand the difference in the back contact force during the two postures for the same activity. For the supine model, the contact force

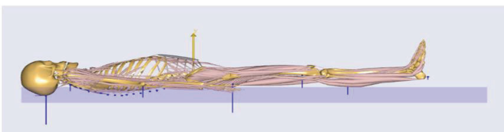


Fig.7. Subject in supine posture

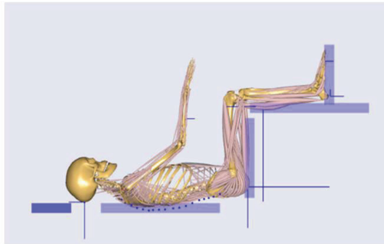


Fig. 8. Subject in semi-supine posture

model was added separately via a cuboidal contact mat as shown in Fig. 7, as explained separately in following section. In the sitting model, contact points were added via a seat model as shown in Fig. 8.

Discrete contact nodes were added on head (1), arms (2), pelvis region (8), thighs (4), legs (2) and feet (4) with contact strength of 10000N and distributed contact nodes on back region based on gird convergence as covered in the next section. The constraints of the model were rectified so that the model is both kinematically determinant and kinetically solvable by the chosen muscle recruitment criterion without over constraining or making the system in determinant.

The obtained model is then simulated and then the force on back contact points is compared with the experimental data.

D. *Grid Convergence and Configuration in AMS for Supine*

In musculoskeletal modelling using AnyBody, grid convergence for contact forces, especially in models with discrete contact nodes like backrest pressure points has to be handled sensibly as:

- Force distribution is sensitive to the node density.
- Max force location can vary with mesh resolution, making direct comparison complex.
- Solving nonlinear equilibrium equations, can have minor node changes that can lead to significant redistribution of load.

Therefore, a convergence based on average back pressure was undertaken as this gives an idea of pressure resolution

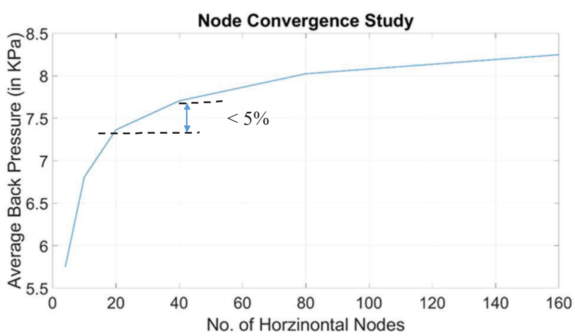


Fig. 9. Node convergence study for determining number of horizontal nodes

stability. Convergence in average pressure per node also indicates mesh independence. As less than 5% is observed

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when the mesh size is changed from 20 to 40 in Fig. 9, hence 20 horizontal nodes were selected for the simulations.

The grid convergence above facilitated the number of horizontal nodes for each point on the back from T1 vertebrae to Sacrum (Fig. 10) with 18 horizontal rows (T1-T12, L1-L5 and sacrum) and 20 contact points per row as determined from the grid convergence study.

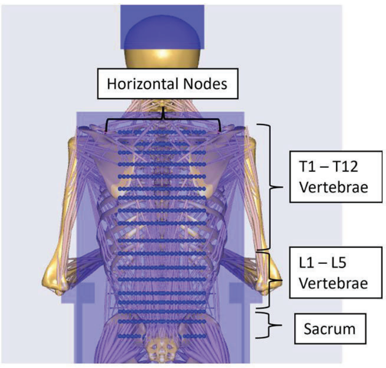

Fig. 10. Horizontal nodes on supine visualized in Anybody software

E. *Contact Modelling in AMS*

The contact force was computed utilizing the cylinder-of-influence principle. A contact node is deemed active if it resides within a predefined cylindrical region surrounding the seating surface. This region is characterized by a radius limit (Fig. 11) and maximum and minimum height boundaries, defined as r_{inf}, h_{max} and h_{min} respectively.

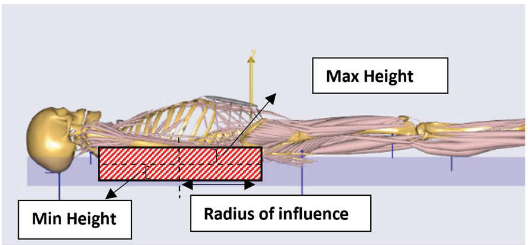

Fig. 11. Schematic of AMS contact force activation based on cylindrical influence

The contact strength function, $S(r,z)$ is modelled as a rectangular function where r and z are the horizontal and vertical distance from the center of environmental object (for e.g. mat for supine simulations) respectively, applying full force when the node is inside the cylinder and zero force when outside, as shown in (1) and (2).

$$S(z) = \begin{cases} S_{opt}, & h_{min} \leq z \leq h_{max} \\ 0, & z < h_{min}, z > h_{max} \end{cases} \quad (1)$$

$$S(r) = \begin{cases} S_{opt}, & r \leq r_{inf} \\ 0, & r > r_{inf} \end{cases} \quad (2)$$

where S_{opt} is the optimized Strength.

During simulation, node positions and corresponding normal force values were extracted from AMS via scripting.

These data were subsequently post-processed in MATLAB to generate simulated contour plots representing the normal force distribution on the back. Since nodes maintained a constant vertical height, force values did not vary along horizontal lines. Force profiles were extracted and compared with pressure mapping data for validation purposes. The maximum force value obtained was employed as a quantitative metric for model validation.

IV. RESULTS AND DISCUSSION

A total of eight pressure contour plots were analyzed, involving two subjects, two postures, and both experimental and simulation data sets. The results indicate that AMS effectively captures the spatial distribution patterns of contact forces across the back surface.

To refine the model, six parameters were identified: maximum height, minimum height, radius of influence, contact strength, number of horizontal rows, and nodes per row (Table 2). The horizontal rows were fixed at 18, corresponding to vertebral levels T1–T12, L1–L5, and the sacrum. The number of nodes per row was determined through a node convergence study. The remaining parameters were iteratively adjusted to ensure close alignment between simulated force contours and experimental trends, including peak force magnitudes.

TABLE 2. OPTIMISED PARAMETERS FOR VALIDATION

Parameter	Supine Posture	Semi-Supine Posture
Max Height (h_{max})	0.1 m	0.1 m
Min Height (h_{min})	–0.1 m	–0.1 m
Radius of Influence (r_{inf})	2 m	2 m
Strength (S_{opt})	10000 N	10000 N
# Horizontal Rows (Back)	18	18
# Nodes per Row	21	21
# Total Nodes	378	378

Simulation results (Figure 13) revealed force concentration hotspots near the sacral region, consistent with experimental observations. The model also captured a hotspot near the shoulder region; however, due to the uniform vertical height of nodes, the load distribution resulting from left-right spinal curvature was not represented. Simulations for the semi-supine posture similarly identified high load concentrations on the sacrum.

Comparative analysis of supine and semi-supine contours (Fig. 12 to Fig. 15) demonstrated increased force concentration on the sacrum in the semi-supine posture, a trend corroborated by peak force values reported in Table 3. This in reflects load redistribution from the legs to the back in the semi-supine position. An average error of 13.9% was observed between simulated and experimental data. This discrepancy may be reduced in future models.

TABLE 3. COMPARISON OF EXPERIMENTAL AND SIMULATION MAXIMUM NORMAL BACK FORCE FOR VALIDATION

Subject	Posture	Experimental Max Force (in N)	Simulation Max Force (in N)	Error (in %)
S1	Supine	4.91	4.57	6.92
S2	Supine	5.34	3.80	28.83
S1	Semi Supine	5.50	5.22	5.09
S2	Semi Supine	5.50	4.67	15.09

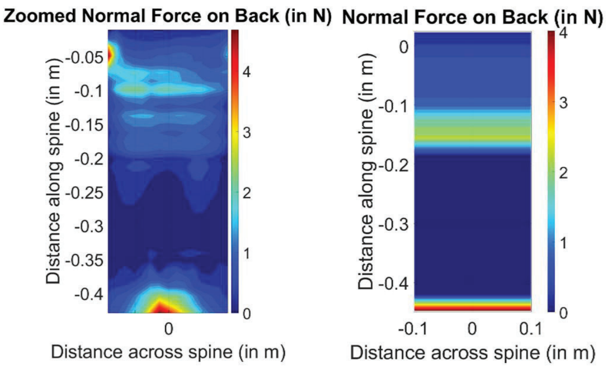

Fig. 12. Experimental Normal force contour using pressure mapping and Simulated Normal force contour on AnyBody on back for Subject 1 in supine posture

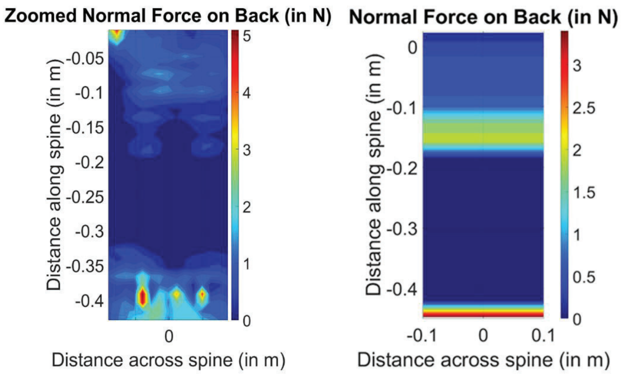

Fig. 13. Experimental Normal force contour using pressure mapping and Simulated Normal force contour on AnyBody on back for Subject 2 in supine posture

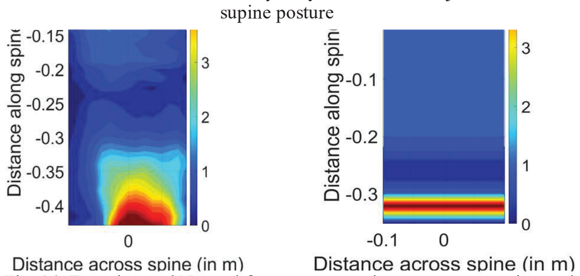

Fig. 14. Experimental Normal force contour using pressure mapping and Simulated Normal force contour on AnyBody on back for Subject 1 in semi-supine posture

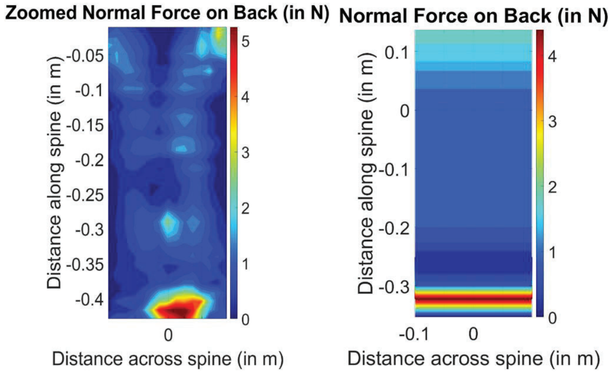

Fig. 15. Experimental Normal force contour using pressure mapping and Simulated Normal force contour on AnyBody on back for Subject 2 in semi-supine posture

The variation in maximum normal forces between postures can be attributed to the redistribution of body weight due to torso inclination in semi-supine positioning. Subject S2 showed a 28.83% error in the supine posture, likely due to inter-individual differences in back contour and load distribution, which were not fully captured by the uniform-height node, Caucasian muscle model and lack of subject-specific strength scaling assumption. Future iterations of the model will address this by applying a 3D surface fitting to better match body contours.

V. CONCLUSION

This validation study establishes a foundation for advancing musculoskeletal modeling under more dynamic conditions. Future work will involve varying joint angles at the hip, knee, and neck to simulate responses under high-g loads, and transitioning to Hill-type muscle models to achieve physiologically accurate muscle behavior.

Integration of electromyography (EMG) data and instrumented seat sensors is planned to enable comprehensive full-body model validation. Additionally, future AMS implementations aim to incorporate three-dimensional spinal curvature and soft tissue compliance to enhance model fidelity.

In conclusion, this study successfully validates the AnyBody contact force model for supine and semi-supine postures using pressure mapping as a reference. Despite inherent model simplifications, the results demonstrate strong agreement in both spatial distribution and quantitative force metrics. The validated AMS model is now suitable for application in subsequent research phases focused on crew posture design, ergonomic optimization, and acceleration load assessment in the human spaceflight program.

VI. FUTURE WORK

Ongoing work will focus on integrating dynamic loading conditions into the musculoskeletal model, especially during launch and re-entry phases where high acceleration is encountered. Varying joint angles at the hip, neck, and knees will be simulated to capture postural adaptation under G-loads. Integration of electromyography (EMG) sensors will allow for concurrent validation of muscle activation levels and force prediction. Moreover, the model will be enhanced by including spinal curvature geometry and soft tissue compliance. Long-term, this modeling framework will be extended to accommodate a larger sample size, include female analogs, and incorporate anthropometric scaling for Indian astronaut candidates. These improvements will ultimately support ergonomic seat design and crew safety assessments in human spaceflight programs.

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