Spinal Stiffness in Prone and Upright Postures During 0–1.8 g Induced by Parabolic Flight

Jaap Swanenburg; Michael L. Meier; Anke Langenfeld; Petra Schweinhardt; B. Kim Humphreys

INTRODUCTION: The purpose of this study was to analyze posterior-to-anterior spinal stiffness in Earth, hyper-, and microgravity conditions during both prone and upright postures.

CASE REPORT: During parabolic flight, the spinal stiffness of the L3 vertebra of a healthy 37-yr-old man was measured in normal Earth gravity (1.0 g), hypergravity (1.8 g), and microgravity (0.0 g) conditions induced in the prone and upright positions. Differences in spinal stiffness were significant across all three gravity conditions in the prone and upright positions. Most effect sizes were large; however, in the upright posture, the effect size between Earth gravity and microgravity was medium. Significant differences in spinal stiffness between the prone and upright positions were found during Earth gravity and hypergravity conditions. No difference was found between the two postures during microgravity conditions.

DISCUSSION: Based on repeated measurements of a single individual, our results showed detectable changes in posterior-to-anterior spinal stiffness. Spinal stiffness increased during microgravity and decreased during hypergravity conditions. In microgravity conditions, posture did not impact spinal stiffness. More data on spinal stiffness in variable gravitational conditions is needed to confirm these results.

KEYWORDS: stiffness, spine, microgravity, hypergravity, lumbar spine.

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Spinal stiffness is an important kinesiological parameter of spinal function. In the clinical setting, spinal stiffness measurement is commonly used to evaluate whether a joint is hypo- or hypermobile.[17] The orientation of the spine toward gravity, voluntary muscle contraction, gravity, and changes in loading directly impact spinal stiffness,[2,16,18] e.g., a 10% maximal voluntary contraction activity of the erector spinae increases spinal stiffness to a posterior-anterior force by 12%.[16] The activity of the multifidus muscle increases when posture changes from prone to upright.[2] In an upright posture, a greater degree of muscle activation is needed because the spine must stabilize toward gravity. In the prone position, most of this stability is achieved from passive muscle stiffness, inherent tension from the osteoligamentous subsystem.[18] During daily activities, the human spine is continuously challenged by changes in loading. Changes in spinal load also lead to changes in joint torque, somatosensory feedback, and neuromuscular activity.[13] Furthermore, increase in the spinal load results in increased muscle activity.[2,18]

The assessment of spinal stiffness plays an important role in clinical analysis and diagnostics, management, and treatment of patients, particularly those with low back pain (LBP).[6] Pain and anxiety can also lead to increased spinal stiffness due to cocontraction of lumbar muscles.[4] In contrast, segmental lumbar instability can lead to decreased spinal stiffness.[10] With respect to varied gravitational environments, exposure to microgravity (MG) has been linked to increased incidence of LBP.[14] Sayson and Hargens[14] hypothesized that reduced axial load in the MG environment causes excessive fluid influx in the intervertebral discs, leading to the expansion of the discs, which likely stimulates the meningeal branches of the spinal nerves, thereby leading to discogenic LBP.[14] However, Chang et al.[3] observed minimal changes in the disc height or swelling of the

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spine during MG conditions. They hypothesized that factors other than swelling of the intervertebral disc lead to LBP.[3]

The orientation of the spine toward gravity and MG during loading conditions is a risk factor for the development of LBP. However, information regarding the interaction of these factors remains unclear. In particular, a systematic assessment of spinal stiffness under different gravity conditions and postures is needed. Importantly, a better understanding of spinal stiffness-associated postures during different gravity conditions may lead to novel insights into the stabilization mechanisms of the lumbar spine, which are important for all aspects of spinal function. The objective of this study was to assess the changes in posterior-to-anterior spinal stiffness in prone and upright postures during MG, hypergravity (HG), and Earth gravity (EG) conditions induced by parabolic flights.

CASE REPORT

The subject who participated in this case study was a healthy, 173-cm tall, 37-yr-old man weighing 75 kg. The participant passed the required aviation medical screening and provided a written informed consent to participate in this study. Experiments were conducted during the second Swiss Parabolic Flight Campaign aboard the Airbus A310 ZERO-G (operated by Novespace, Bordeaux, France). The total duration of the 1-d flight was 3 h and comprised 15 zero gravity parabolas. The ethics committee of the Canton of Zurich approved this study (KEK-ZH-NR: 2016-01,055).

A single-case repeated-measures study design was used to assess the changes in spinal stiffness in prone and upright postures during three different gravity conditions. Spinal stiffness measurements in prone and upright postures were performed during five parabolas each. The course of one parabola started with a horizontal and level flight with normal EG (1 g), followed by a steep climb flight that induced 20 s of HG (1.8 g). Next, the airplane "pushed over" the top, which began the 22 s of MG (0 g) of the parabolas. Subsequently, a second HG phase followed, then finally, return to normal flight level. This second HG phase was not measured in this study. The test subject was familiarized with the test procedures prior to the flight to assure repeatability and reproducibility. Furthermore, 30 min prior to the flight, the subject and other research participants were administered scopolamine (Kwells; hyoscine hydrobromide, 300 μg) to prevent motion sickness. The administration of scopolamine does not interfere with sensorimotor skills associated with neuromuscular control.[12]

Measurements of spinal stiffness in changing gravity conditions required a mobile and wearable device to account for Newton's third law. A full-body harness with an impulse head fixed on an aluminum structure was developed for this study to generate the reaction force (**Fig. 1**).

The computer-assisted analytical device "PulStar" (Function Recording and Analysis System device PulStarFRAS, Sense Technology, Inc., Pittsburgh, PA) with good-to-excellent reliability was used to measure posterior-to-anterior spinal stiffness.[8]

Fig. 1. Test subject wearing the measurement device prior to experimental conditions.

The instrument measures tissue compliance according to the concept of impulse-response. A force of 80 N was applied from the device to the L3 spinous process. To trigger the measurement, a preload of 18 N was applied to overcome possible confounders caused by the soft tissue components between the device and spinous process. This preload was generated by a balloon behind the measurement device, which was connected with a hand air pump operated by the measurement assistant. The measurement setup was connected using a cable with the control unity and a laptop, which were secured on the floor of the airplane. Blinding of the measurement assistant was not possible because he also experienced the gravity conditions. A video that captured all the measurements was used to confirm the position sequence of the participant.

Pre- and in-flight familiarization procedures were conducted to minimize the subject's anxiety and to precondition the soft tissues over the previously-identified L3 spinous process. Because respiration can affect spinal stiffness measurements, the subject was instructed to inhale and exhale comfortably, and then hold his breath at the end of a normal exhalation. The subject was secured by tethers between the full-body harness of the measurement device and the aircraft to prevent drifting away in MG. To reduce the risk of falling during HG, the subject was further secured using a strap between the harness and an attachment point on the ceiling of the airplane.

Distribution testing for normality was done using the Shapiro-Wilk test. Visual analysis was performed by plotting all the data points and describing the trends in the data between the different gravity conditions and posture positions. Confidence intervals (CI) of 95% with the means for graphical data presentation were plotted for each gravity condition and posture position. The differences across all three gravity conditions were explored using the Kruskal-Wallis test in both prone and upright positions. The Mann-Whitney *U*-tests were used as post hoc. The differences between the posture positions were tested using the Mann-Whitney *U*-tests. Cohen's d was used to calculate effect sizes. The scale of the effect sizes included small (0.2), medium (0.5), and large (0.8). The data was transferred, stored, and analyzed using the IBM SPSS 23 statistical software package (SPSS Inc., Chicago, IL).

We successfully conducted 116 posterior-to-anterior spinal stiffness measurements, with 58 each in the upright and prone positions. The data during the EG condition in the upright position was not normally distributed. Visual inspection showed that a majority of the stiffness data points were lowest under the HG condition. The data points under the MG condition showed the highest stiffness values (**Fig. 2** and **Fig. 3**).

The 95% CIs are shown in **Fig. 4**. Upright and prone postures showed the same pattern of spinal stiffness between the gravity conditions. The differences across all three gravity conditions were significant in both the upright ($H = 38.568$, $df = 2$, $N = 58$, $P < 0.001$) and prone ($H = 46.750$, $df = 2$, $N = 58$, $P < 0.001$) postures. Post hoc tests showed significant differences between all the gravity conditions (**Table I**). Significant differences in spinal stiffness between the upright and prone positions were found during the EG ($P < 0.001$) and HG ($P < 0.001$) conditions, whereas no difference was found between the upright and prone positions during the MG ($P = 0.640$) condition. All but one test showed a large effect size; the effect size between the EG and MG conditions in the upright position was medium. All results are shown in Table I.

DISCUSSION

Based on repeated measurements of a single individual, the results showed detectable changes in posterior-to-anterior spinal (L3) stiffness between varying gravity conditions. Patterns in spinal stiffness changed between the different gravity conditions but were similar in both the upright and prone positions. We confirmed a greater degree of spinal stiffness in the upright position than in the prone position during the EG and HG conditions. During the MG condition, spinal stiffness in the upright and prone positions was the same, possibly because no gravity or axial load acts on the spine in this condition. Nevertheless, increased spinal stiffness during the MG condition was an unexpected result. During the MG condition, the extensor muscles of the lumber spine are less activated due to the missing gravity;[3,9] therefore, theoretically, spinal stiffness should have been reduced.

There are several possible explanations for the increased stiffness during the MG condition. First, the stiffness could be a reaction to the sudden change in gravity, which could have led to a safety co-contraction of the lumbar muscles that secured spinal integrity. Brown et al. examined the trunk muscle activity of sudden unloading of the hands in the sagittal plane and found increased specific spine muscle activation that increased spinal stability.[1] In our study, the co-contraction of the trunk muscle should have increased. We did not measure muscle activity, but an earlier study showed a decrease in dynamic muscle stiffness of the gastrocnemius and erector spinae muscles in the MG condition during a parabolic flight.[15] This decrease in muscle activity contradicts our first possible explanation.

Another possible explanation relates to the activity of the psoas major muscle. Previous studies have shown that the size of the psoas muscle does not change significantly during spaceflight, in contrast to the degeneration of the spinal extensor muscles.[3,9] Due to missing axial load during the MG condition, the extensor muscles cannot stabilize the spine.[3] Therefore, to assist spinal stability, the antagonistic lumbar

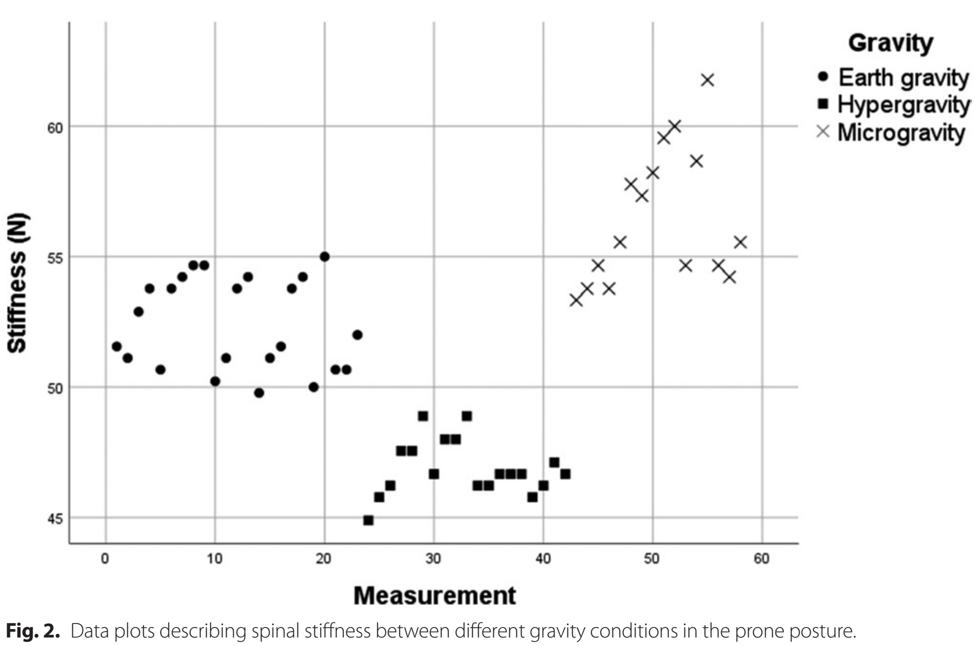

Fig. 2. Data plots describing spinal stiffness between different gravity conditions in the prone posture.

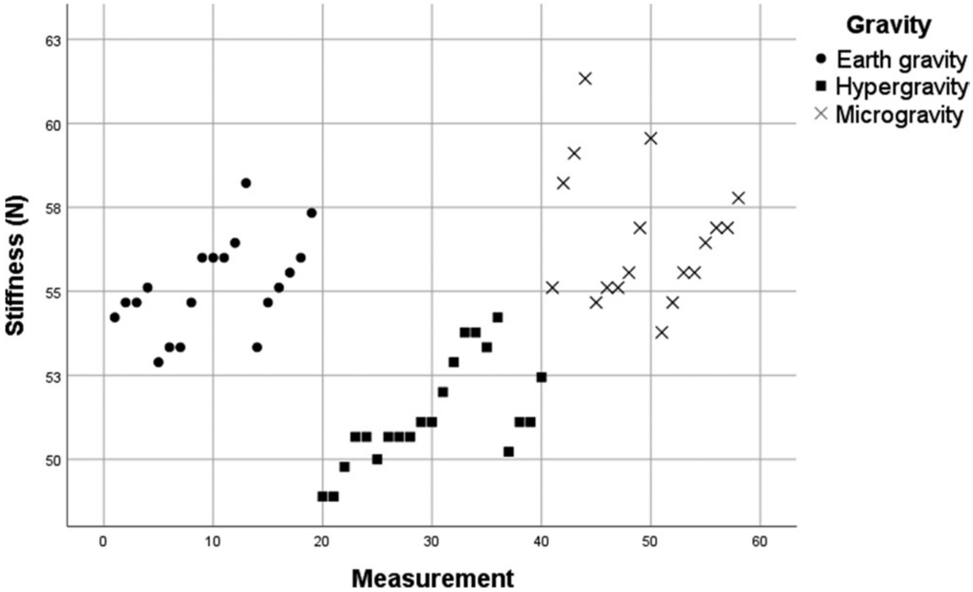

Fig. 3. Data plots describing spinal stiffness between different gravity conditions in the upright posture.

flexor muscles (e.g., psoas muscle) may contract. A possible counter-argument to this is with respect to the flattening of the lumbar curvature during space missions.[3] It has been argued that the activity of the psoas muscle increases lumbar curvature. However, the influence of the psoas muscle on lordotic curvature is unclear. Penning suggested that the psoas muscle stabilizes the lordotic lumbar spine in an upright position by adapting its contraction to the momentary degree of lordosis imposed by factors external to the lordosis, such as weight-bearing.[11]

One more possible explanation is that the results are coincidental because this was a single-case study. However, this seems less plausible as the changes between gravity conditions were similar between both the upright and prone positions.

Spinal stiffness in the HG condition was lesser than in the EG condition in both the positions. This decrease in stiffness was unexpected as the central nervous system responds to perturbations of the spine with pre-activated muscles, feed-forward muscle contraction, or afferent feedback with increased stiffness and muscular activation.[7] Higher trunk muscle activity increases compressive forces acting on the spine,[1] which causes increased spine stiffness. Additionally, in-vitro tests showed an increase in spinal stiffness along with increased axial load,[18] and these tests displayed the passive stability of the specimen. Because passive stabilization of the spine plays only a minor role, the increase in passive stabilization of spinal stiffness during the HG condition may have been negligible. Further, the increase in gravity was expected by the subject; hence, the anticipatory adjustment may have resulted in increased muscle activity.[1] However, opposite results were found in the MG condition during the parabolic flight.[15] This is potentially explained by the fact that only L3 was measured; spinal stiffness may differently change different segments of the spine with changing gravitational conditions. The full-body harness could have influenced the measurements. If it had an influence on stiffness, it would be the same in all gravitational conditions.

Clinically the findings of this study are interesting. A possible constant co-contraction of the psoas in MG might lead to muscle fatigue, which is associated with increased spinal instability,[5] thereby leading to injury intolerance and lower back pain.[19] The observation that some astronauts report relief of lower back pain when they are in a fetal tuck position,[20] which allows the psoas muscle to relax, supports the assumption that constantly co-contracted flexor muscles could contribute to lower back pain in microgravity. Clarifying the potential clinical relevance of these changes in spinal stiffness during HG and MG will require additional research.

Our study showed that, during the MG condition, spinal stiffness increased, with no difference between the prone and upright positions. These results indicate changes in the spinal stabilization strategy with changing gravitational conditions. It is important to verify our study results with a larger sample size and with more measurements. Future research

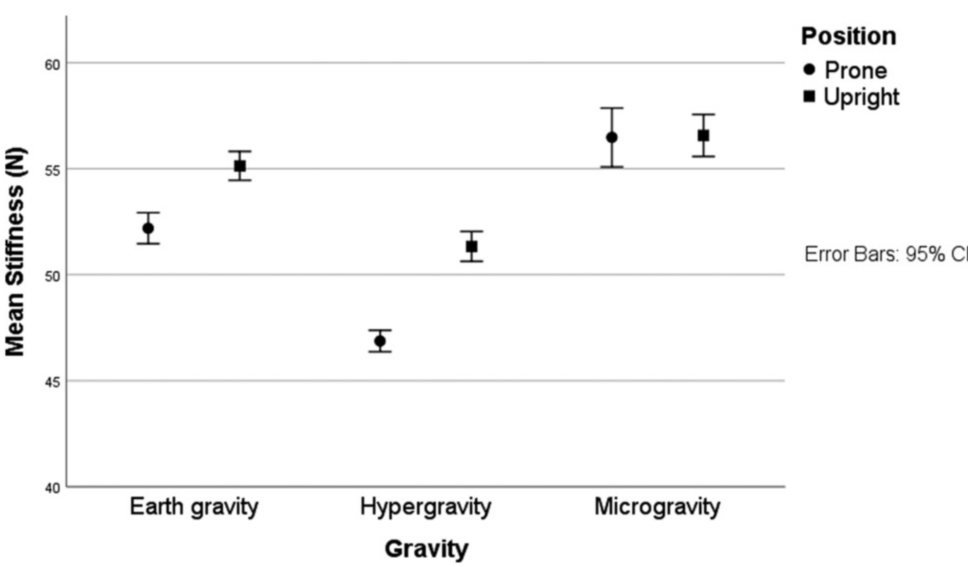

Fig. 4. Spinal stiffness of L3: mean and 95% confidence interval for each gravity condition and posture.

Table I. Mean Values of Spinal Stiffness, Difference Tests, and Effect Sizes Between the Three Gravity Conditions.

				EG–HG			EG–MG			HG–MG		
	EG (1 g)	**HG (1.8 g)**	**MG (0 g)**	***P***	**d**	**ES**	***P***	**d**	**ES**	***P***	**d**	**ES**
Prone Mean (SD)	52.19 (1.69)	46.88 (1.05)	56.48 (2.60)	<0.001	3.295	0.855	<0.001	2.017	0.710	<0.001*	3.270	0.853
Upright Mean (SD)	55.13 (1.41)	51.37 (1.53)	56.57 (1.99)	<0.001	2.585	0.790	0.027	0.782	0.360	<0.001*	3.177	0.846

EG = earth gravity; HG = hypergravity; MG = microgravity; *N* = Newton; *P* = comparison by Mann–Whitney *U*-test; d = Cohen's d; ES = effect size.
* Significant, $P < 0.05$.

should combine spinal stiffness measurements with muscle activity data of the lumbar extensors and flexor muscles, thus providing clinically important information on spinal stabilization mechanisms.

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