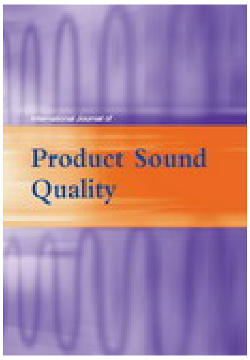

International Journal of Product Sound Quality

ISSN online: 1742-6766 - ISSN print: 1742-6758
https://www.inderscience.com/ijpsq

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DOI: 10.1504/IJPSQ.2023.10058426

Article History:

Received:	07 April 2023
Last revised:	29 May 2023
Accepted:	22 June 2023
Published online:	28 September 2023

Design and evaluation of a new composite spine support

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Abstract: Many patients suffering from back deformity, such as scoliosis, kyphosis and Scheuermann's diseases can benefit from a novel spine support designed to non-invasively correct posture in the entire spinal column. The proposed model, constructed of polymer sleeves and a solid support beam, is light and strong and allows for size and position adjustments. Hence it can be used for any patient presenting with moderately distorted posture. The proposed support is based on previously designed composite finger and foot supports and was selected to have the least effect on the user's everyday life while still providing correction for the patient. In this proposal, the solid support beam is constructed of aluminium or steel, allows rotatability and its length can be adjusted to accommodate the height of various people. Computer simulations using SolidWorks© have been performed to validate the maximum displacement in the beam and also the maximum Von-Mises stress developed.

Keywords: spine; structure; orthosis; finite element analysis; composite.

Reference to this paper should be made as follows: Nasseri, S., Jonaidi, M., Kortobi, S., Plowman, T. and Williams, G. (2023) 'Design and evaluation of a new composite spine support', *Int. J. Product Sound Quality*, Vol. 1, No. 1, pp.78–90.

Biographical notes: Simin Nasseri obtained her PhD in Mechanical Engineering from the Sydney University. She has been working at the Kennesaw State University (KSU) since 2006. She has about 25 years of academic/industry experience. In addition to journal/conference papers and book chapters, she has published a book titled: *Solving Mechanical Engineering Problems with MATLAB*. Her research experiences are related to biomechanical engineering (artificial organs and soft tissue rheology), manufacturing, rheology and viscoelasticity, polymer processing, computational mechanics, robotics, and micromachinery. She has won many fellowships, awards and grants. In 2019, she received the KSU distinguished professor award, for excellence in teaching, research and service.

Mohammad Jonaidi obtained his PhD from the Sydney University and currently working at the Kennesaw State University. During 38 years of research and industry professions, he has been involved in analysis and design of complex structural projects such as: FEA of high-rise buildings/steel structures, floor vibration for concrete slabs/pedestrian bridges, serviceability vibration analysis of high-rise buildings, earthquake engineering, post-tensioned concrete structures, nonlinear and buckling analysis of thin-walled cylinders, analysis of long span spatial steel structures, analysis of glazing façade, below grade shoring walls, retrofit of concrete structures using fibre reinforced polymers (FRP), and the strengthening of structures to resist progressive collapse.

Salim Kortobi is currently pursuing his BSc in Mechanical Engineering with minors in Engineering Design Graphics and Manufacturing Engineering Technology at the KSU. He is a Certified SolidWorks Expert in Mechanical Design (CSWE). He has extensive knowledge in 3D printing and has used that knowledge to assist in equipment procurement and the establishment of the BioMechanical Engineering Lab at KSU. As Dr. Simin Nasseri's research assistant, his work has included various research projects including the finger, foot and spine supports. He also has used his knowledge in computer aided engineering (CAE) to run various SolidWorks simulations as part of the BME research.

Timothy Plowman is graduated from the Auburn University with a BSc in Mechanical Engineering and a minor in Industrial/Graphic Design. In 2020, he enrolled at the KSU to further his education by pursuing a Master's in Mechanical Engineering. He joined Dr. Simin Nasseri's research team where he worked as a research assistant in the BME research group, performing extensive computer simulations using SolidWorks for foot and spine supports. He is currently works as a quality engineer for Stimlabs, a local regenerative medicine company, where he uses Lean Six Sigma methods to analyse and improve equipment processes and write and execute equipment validations.

George Williams obtained his BSc in Mechanical Engineering from the KSU in 2021. He has worked with Dr. Simin Nasseri's BME team to develop non-invasive orthoses for treating musculoskeletal pathologies; and with Dr. Mohammad Jonaidi to develop novel relief details for column-slab connections in reinforced concrete. As the Former President of Kennesaw

Motorsports, he designed and manufactured performance IC/EV powertrain components for Formula SAE vehicles. He currently works as a mechanical engineer at the Compass Technology Group, LLC, focusing on electromechanical design/drafting, conventional/computational analysis in structural, fluid/thermal/EM systems (FEA, CFD, and CEM), manual and CNC machining, computer-aided manufacturing (CAM), and industrial control systems integration.

1 Introduction

Spinal deformities greatly affect many individuals' daily functions such as general mobility and loss of focus due to back pain. The American Chiropractic Association (2020) reports that approximately 80% of people experience a form of back pain, being the third most common reason for a trip to the doctor's office. Deformities like hyperkyphosis, Scheuermann's disease, and scoliosis have several potential causes. An example is an initial injury that gradually develops into a deformity, possibly complicated by muscle weakening and obesity. It should also be noted that factors like age can affect the tendency to develop deformities. For example, people's joints and bones tend to deteriorate as they age, making them more susceptible to deformities (Katzman et al., 2010). The cause for some back deformities is still unknown. However, the leading cause of back pain is due to poor posture.

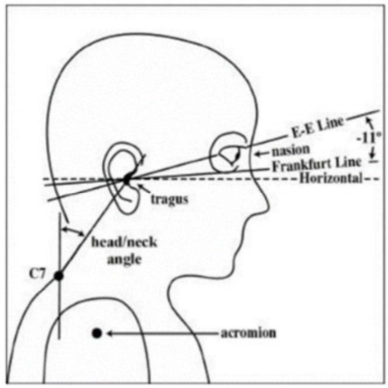
To determine the severity of spinal deformities, some measurements may be taken depending on the presentation. These measurements ascertain the angle of curvature of the spine. As poor posture is one of the leading causes of deformities in the back, Figure 1(a) shows an example of the metrics of posture, like the head/neck angle and head tilt (Ankrum and Nemeth, 2000).

To treat these spinal deformities, different surgical methods are available. These invasive correction methods can cost between \$50,000 to \$180,000 depending on the surgeon and facility costs (Jelcick and Janzen, 2022). There are a variety of non-invasive correction methods available that apply the use of different orthoses. McAviney et al. (2020) conducted a study to determine the effectiveness of spinal orthoses and concluded that these braces might have a short-medium term positive impact for scoliosis patients. However, they determined that the data was of low quality and did not represent a diverse enough population to draw any further conclusions (McAviney et al., 2020).

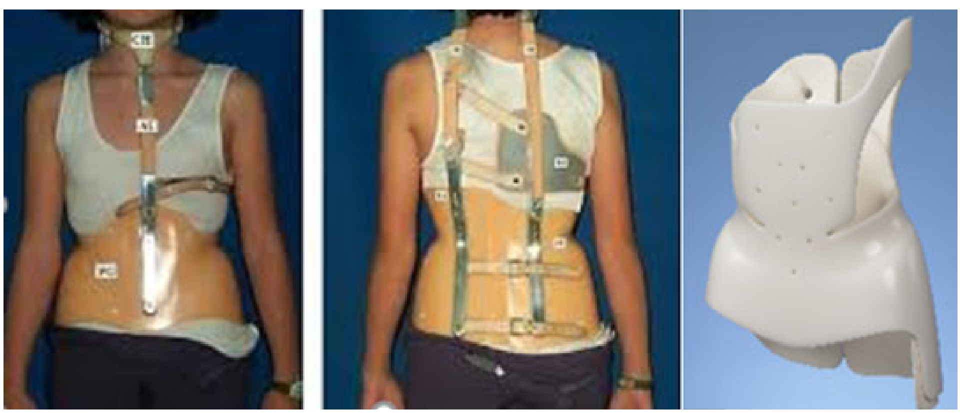
Blount et al. (1958) [Figure 1(b)] created the Milwaukee orthosis. This orthosis is custom made and moulded from the patient's torso. In 1970, Miller and Hall (1970) created a similar device named the Boston brace (also Wynne, 2008). Both orthoses work in a similar way, restricting motion in the direction of the deformity and providing a corresponding corrective force.

Orthopaedic surgeons, Walter Gutowski and Thomas Renshaw, conducted a study on the effectiveness of these two orthoses in patients with kyphosis. The average decrease in deformity angle for patients that used the Boston device was 27%, while the average decrease in deformity angle for patients that wore the Milwaukee brace was 35% (Gutowski and Renshaw, 1988). Lakshmi et al. (2017) conducted research on another device used for spinal correction. The wearable device that they created modifies the user's posture. The user wears a compression shirt and there is a flex sensor attached to the lower back. A microcontroller uses the output of the sensor to determine if the user has poor posture. Then, if the user does not correct their posture, the DC motor on a flex belt is activated and adjusts the user's posture.

Figure 1 (a) Measures of posture (b) Milwaukee and Boston braces (see online version for colours)



(a)



(b)

Another corrective design was researched by Cole et al. (2013). For this design a compression shirt was used as well as elastic tension straps. The tension straps attached to scapular pads and pectoral pads and ran to the waist to provide posture correction. The device was tested on individuals with a relatively high forward head and shoulder angle. The results showed that the device decreased the forward shoulder angle, but not the forward head angle (Cole et al., 2013). Abdoli-Eramaki et al. (2006) created a device to assist the lumbar and thoracic areas without affecting abdominal muscle operation. They found that the device did reduce the potential for back injuries and would also be helpful to workers more safely returning to work after injury to protect them from additional injury due to repetitive lifting tasks (Abdoli-Eramaki et al., 2006).

Imamura et al. (2014) were developing a wearable passive power assist supporter somewhat like a corset, to stabilise the torso called Smart Suit Lite. They constructed a mechanical model to analyse how trunk stabilisation was affected by power assist devices (Imamura et al., 2014). Inose et al. (2017) developed 'AB-wear' to reduce fatigue on waist muscles due to large numbers of Japanese workers experiencing lower back pain. The apparatus used a spring against the upper body which assisted in stabilising the wearer's torso. The apparatus was proven effective with both simulation as well as surface electromyography (EMG) (Inose et al., 2017). Lavender et al. (2012) designed a lift assist that can be integrated with pallet jacks and thereby move through the facility with the workers. It was determined that it had the potential to reduce the risk of back and shoulder injuries (Lavender et al., 2012).

Näf et al. (2017, 2018) developed a special back-support exoskeleton which allowed for a large range of motion while wearing the support and was less hindering and functional. In their device, a passive, parallel elastic torque source provides support at the hip. Their device, however, is bulky and heavy and requires the help of an expert to be adjusted and worn. Patients cannot set the device by themselves (Näf et al., 2017, 2018). Toxiri et al. (2016) analysed a simplified spine support model to determine whether perpendicular to the spine load placement or parallel load placement was more effective in reducing the force on the spine. Their research supported that perpendicular placement was preferred since it greatly reduced spine compression.

In this paper, a simplified back support was introduced consisting of a solid support wrapped in a polymer shell. A finger support was previously designed, fabricated and tested which used the same principles (Nasseri et al., 2018a, 2018b). A composite bunion support was designed and analysed as well (Nasseri et al., 2023). This spine brace was intended to prevent and correct the deformities that may arise out of muscle weakness or habitually poor posture. It is made to provide a straightening corrective force to individuals who may be slouching or have weakness due to an injury, though may not be suitable for major deformities that require strong mechanical assistance. To assist patient comfort, the polymeric shell was intended to be soft and non-intrusive on daily life, while the included straps were adjustable to fit a variety of patients without the costly custom-moulding that other braces require. Extensive SolidWorks modelling confirmed low displacements needed for this device.

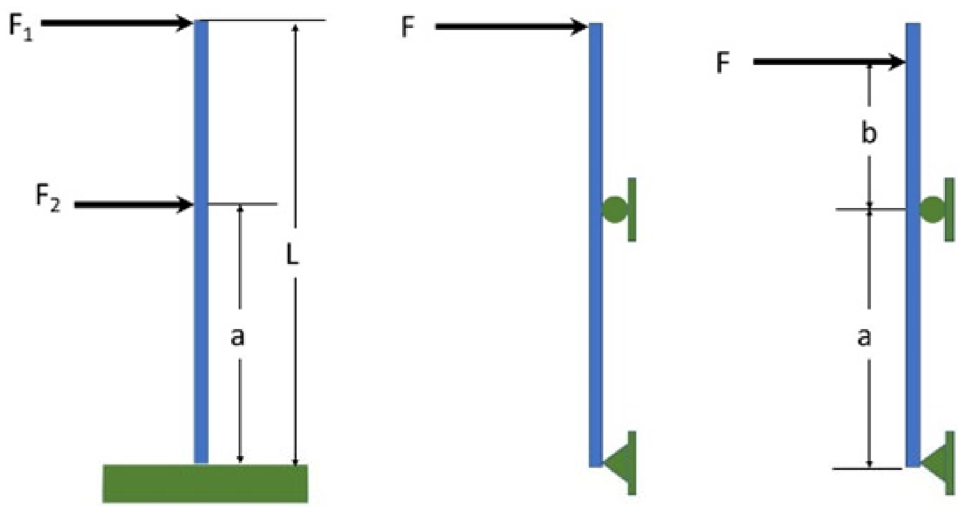
2 Materials and methods

The initial model comprised of an aluminium or steel rod inserted in the polymer shell was treated as a cantilevered beam, assuming that the model was approximated to be fixed at the patient's waist [Figure 2(a)]. The amount of correctional force required to be exerted by the support was estimated at 30 N, based on a lower range of the force exerted on a patient's spine by a Boston brace, and was applied to the top strap of the brace (Van Den Hout et al., 2002). Figure 2 shows images of a cantilever beam with the two forces on the left-hand side.

For a spine exerting a force treated as a concentrated or point load, the following equation can be used to find the deflection caused by a force applied at the end of the metal beam $\delta = \frac{FL^3}{3EI}$, where F is the force in N, L is the length of the rod in mm or distance from the base of the beam to the location of the equivalent point force being exerted, E is the elastic modulus of the metal (a measure of stiffness) in GPa and I is the area moment of inertia or resistance against bending in mm^4. The alloy steel which has been selected for this research has a modulus of elasticity (E) of 210 GPa and the 6061 aluminium alloy has a modulus of elasticity (E) of 69 GPa. The area moment of inertia (I) for the shape of this steel rod can be calculated with the circular cross section by $I = \frac{\pi d^4}{64}$, where d is the diameter of the rod mm. For a force applied between the two ends of a beam, deflection can be calculated using $\delta = \frac{Fa^2}{6EI}$, where a is the distance from the fixed end of the beam to the location of the applied force [Figure 2(a)]. The method of superposition can be used to apply both equations.

$$\Delta = \sum_{i=1}^{2} \frac{F_i a_i^2}{2EI}\left(L - \frac{a_i}{3}\right) \tag{1}$$

Figure 2 (a) Loading configurations of the inserted rod for the initial cantilever model (b) Revised pin-roller model with force at the top (c) Pin-roller 3rd model (see online version for colours)



(a) (b) (c)

A spreadsheet that determined the maximum deflection experienced by the beam using classical equations was made. Maximum deflection was determined after certain parameters were inputted, namely the magnitude of both forces, length of the beam, diameter of the rod, and modulus of elasticity of the material used. The spreadsheet was then used to create the following multivariable function which accounts for both applied forces and can be used to predict deflection:

Considering the pin-roller model shown in Figure 2(b), $\delta = \frac{FL}{3EI}(L-a)^2$ can be used to predict the deflection of the tip of the rod. However, this equation is modified when the force is not applied to the tip of the rod [Figure 2(c)], which is entered into a MATLAB program to evaluate the deflection values considering various force of F, materials and cross sections (E and I) and lengths (a, b and L).

$$\delta = \frac{F}{6EI}\left(3b^2L - ab^2 - b^3\right) \tag{2}$$

$$\sigma = \frac{32Fb}{\pi d^3} \tag{3}$$

To strengthen our conceptual design of the above multivariable function, a MATLAB program was developed and utilised to validate the results. In addition, a parametric SolidWorks model was created. A finite element analysis (FEA) mechanical simulation was created, using the parametric SolidWorks model and its included simulation package. Using a simplified model consisting of only the central solid support, two loads were applied that matched the magnitudes and estimated positions of our approximated point loads. A beam-simplification model was applied, using a fixed constraint at the lower end, and a parametrised length and load position that updated for several lengths. This allowed the response of the system to be determined efficiently, given multiple support beam lengths.

After evaluating the results, a second model was developed [Figure 2(c)]. In this model, a pin support was considered at the bottom and a roller support was placed towards the middle strap location of the spine support. Later, it was analysed that supports configuration mimics the actual forces that the body exerts on the spine support in a more realistic way.

Table 1 MATLAB program assigned dimensions for the inserted rod for the composite spine support

Total length, L	*Distance of force F (30 N) from the pin*	*Distance of roller from the pin*	*Diameter of the inserted rod, D*
609.61 mm	593.69 mm	338.14 mm	9.525 mm

3 Results

The proposed support was modelled in SolidWorks as a parametric assembly. The first edition of the model included several holes and straps for adjustment on patients of different proportions. One placeholder polymer sleeve was added to approximate the soft padding that would be present on a final model, for improving patient comfort (Figure 3).

The second model was consisted of a metal rod inserted in three sleeves that can be made of steel, aluminium and polymer for the sake of computer simulation. Although, the optimal design would be made of aluminium rod in polymeric sleeves to maintain a light weight. This model was designed to allow the rotation of different parts of the body along the rod with respect to each other (Figure 4). This model has also a very steep learning curved for students who would like to learn advanced computer simulation for composite materials.

Figure 5 shows the results of the simulation for the spine support, considering the support beam to be made of aluminium alloy. The same forces that were mentioned above were used in the simulation. The bending stresses generated are shown and proved to be lower than the yield stress of the given material.

Figure 3 The first model of the spine support comprised of a rectangular metal beam in a polymeric sleeve (see online version for colours)

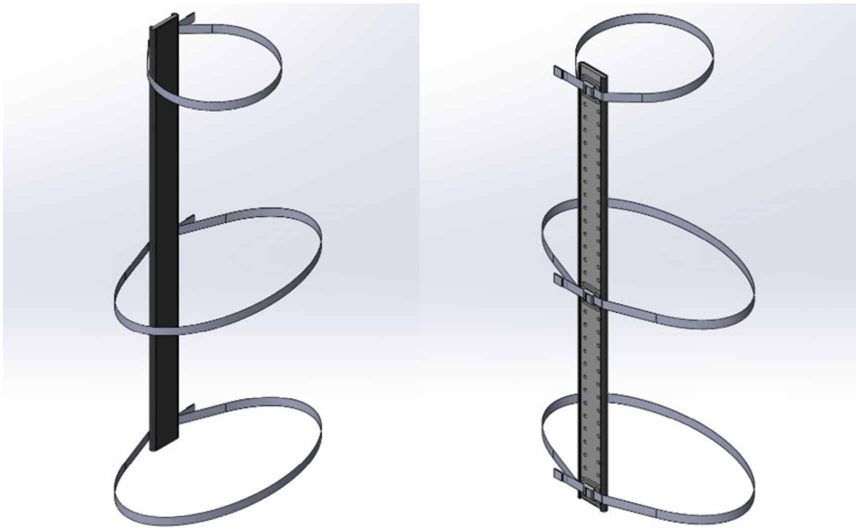


Figure 4 The updated spine support model comprised of a metal rod in three sleeves, with improved rotatability and detailed view (see online version for colours)

Table 2 Yield strength of the materials considered for SolidWorks simulation

Alloy steel yield strength	415 MPa
6061 aluminium alloy yield strength	276 MPa
PETG tensile strength (Z-direction)	11.4 MPa

Figure 5 Plot of simulated Von-Mises stress and displacement for aluminium alloy with PETG sleeves (see online version for colours)

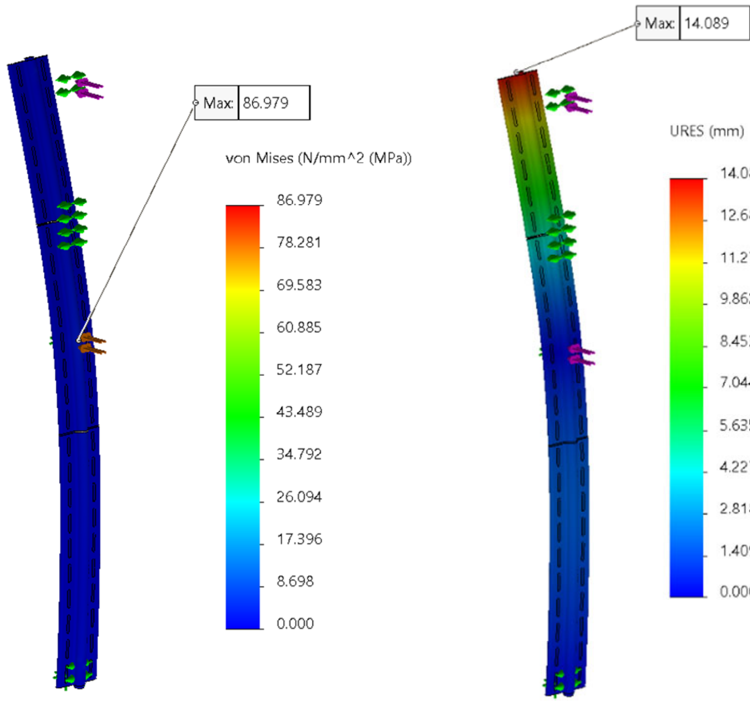


Table 3 Maximum rod Von-Mises stress of spine support with varied rod and sleeve materials

		Sleeve material		
		Steel	*Aluminium*	*PETG*
Rod material	Steel	33.425 MPa	34.201 MPa	91.004 MPa
	Aluminium	N/A	32.089 MPa	86.979 MPa

Table 4 Maximum displacement of spine support with varied rod and sleeve materials

		Sleeve material		
		Steel	*Aluminium*	*PETG*
Rod material	Steel	0.933 mm	1.938 mm	5.093 mm
	Aluminium	N/A	2.613 mm	14.089 mm

Table 5 MATLAB program results for the inserted rod

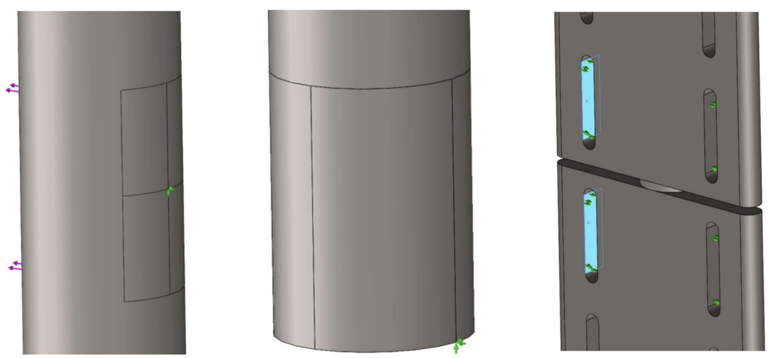
Material	*Deflection (mm)*	*Normal stress (MPa)*
Alloy steel	4.753	90.365
Aluminium	14.466	90.365

After conducting finite element studies on the model of the spine support, it was determined that the initial configuration of the forces and fixtures was incorrect. It was found that the correct loading configuration was a pin support at the bottom and a roller support towards the middle strap location of the spine support. While the forces remained the same as can be seen in Figure 2(c), once the correct loading configuration was ascertained, further computer-generated FEA simulations were conducted to determine the maximum stress and displacement that would be experienced by the spine support during use which can be seen in Tables 3 and 4. The material of the rod and sleeves were also varied throughout the simulation process using aluminium, steel, and PETG, although the preferred material configuration of the spine support was an aluminium rod and PETG sleeves. This material configuration was preferred in order to maintain a lightweight design, ease of manufacturing, and to reduce cost.

4 SolidWorks simulation and MATLAB program methods and comparison

The values listed in Tables 3, and 4 were determined using a SolidWorks static simulation and validated using a custom MATLAB program (Table 5).

Figure 6 Fixtures on updated spine support (see online version for colours)



In order to realistically simulate the stresses and displacements that would be exhibited by the spine support, a SolidWorks static simulation was utilised using the following method:

- To simulate a pin-roller constraint, face divisions were made to split the cylindrical face of the rod creating an appropriate region that the constraints could be applied to, which can be seen in Figure 6.
- The pin constraint was achieved by constraining translations at the lower vertex in the *x*, *y*, and *z* directions as well as two rotations, which then only allowed the rod to rotate about the vertex in the bending plane.
- The roller constraint was achieved using a similar method; however, the only difference was that the rod was free to translate in the *z* (longitudinal) direction.
- To prevent the sleeves from rotating about the rod during the simulation, faces located inside the slots were constrained only allowing motion of the sleeves in the bending plane.

- To ensure an accurate simulation a non-penetration condition was applied to all components in the spine support assembly.
- The two loads mentioned previously were applied to the rod parallel to the bending plane.
- Using the constraints and loads, the simulation was then performed.

In order to validate the results of the SolidWorks simulation, the MATLAB program mentioned previously, was modified to reflect the new model and after its utilisation, the results concurred with the SolidWorks simulation (Table 5).

5 Discussion and conclusions

Corrective devices for spinal deformities are a subject matter that has been explored widely by the research community. However, a device that can correct deformities in the whole spine, while offering comfortability, is scarce in practice. This proposed spine support model would expand the capabilities or characteristics that current devices offer.

The goal of this effort is to create a spinal support that the user can comfortably wear daily. The support should be able to correct the user's deformities by applying a corrective force and still allow for user activity. This new spinal support design incorporates a solid metal rod at its core with three polymer sleeves encasing it which can freely rotate about the rod. The three adjustable straps of the support attach to a patient's waist, chest, and head, to apply the corrective forces to the patient's spine. The sleeves also have many slots for height adjustment of the straps.

The spine support was modelled using SolidWorks and evaluated using SolidWorks simulation to determine the amount of stress and displacement that would be experienced by the support while providing spine stability to patients. A custom MATLAB program was developed and then used to validate the outcome of the SolidWorks simulation which was found to be accurate. The following facts should be considered:

- The MATLAB program considers only the inserted metal rod, whereas the Solidworks model is for the entire rod and three sleeves. However, the stress and displacement values are comparable between the MATLAB results and the metal rod and PETG sleeves. This is because the polymeric sleeves are not connected to each other, and the polymer stiffness is negligible in comparison to the one of aluminium or steel.
- MATLAB program considers the normal stress values, whereas the reported stress values are the Von-Mises stresses in solid model. Since shear stresses are significantly low compared to normal stress for this composite structure, presenting the Von-Mises stresses is acceptable.

To further test the support, it is recommended that a model be fabricated and mechanically tested to further confirm the simulated results. By this testing, it could be determined how the materials (polymeric shell and steel support beam) withstand the daily use of the device. A fabricated model will demonstrate any issues with the modular characteristic of the device. As the device should be worn daily, a fatigue analysis could be helpful in determining how the device responds to cyclic loading and general wear and tear.

The authors of this work have determined that a modular spinal support that can be used for daily fixture would benefit spinal deformity patients. Furthermore, this research should welcome other researchers to manufacture and test similar devices to broaden availability and function of spinal supports.

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