Soft Active Dynamic Brace for Spinal Deformities

Athar Ali[1][a], Vigilio Fontanari[1][b], Marco Fontana[1][c] and Werner Schmölz[2][d]
[1]*Department of Industrial Engineering, University of Trento, Italy*
[2]*Medizinische Universität Innsbruck, Austria*

Keywords: Dynamic Brace, Scoliosis, Corrective Orthosis, Twisted String Actuator, Spinal Exoskeleton.

Abstract: Scoliosis is a 3D deformity of the spine which not only limits the daily activities but in severe cases results in damaging the musculoskeletal, respiratory and nervous system. A conventional way to treat spine deformity is to wear braces. Braces are usually static, rigid and passive and they do not allow the mobility to the spine. This causes the issues of spine stiffness and weakening of the muscles around the spine, which results in other spine complexities such as the flat back. In this study, we have developed a soft active dynamic brace which not only applies the 3D corrective forces but also allow the mobility to the spine. The brace applies the corrective forces using elastic bands, whose tension is being controlled using lightweight twisted string actuation (TSA) mechanism. TSA generates a higher pulling force using low torque motors, which not only reduce the weight of the device but also the metabolic cost.

1 INTRODUCTION

Scoliosis is an abnormality of the spinal curve and every year over 600,000 people are being treated with this disease in United States (Ogilvie, 2010). Patients with scoliosis feel comfortable in the deformed pose and with the growth of the spine in the wrong posture, the deformity or the cob angle also increases. The conventional way to treat the spine deformity is to use braces. A brace is mostly recommended to the adolescence patients whom spine is still growing and their cob angle is less than 30-40^{o}. If the cob angle is greater than 40^{o} than surgery is imminent(Zaina et al., 2014). Several braces have been developed in the mid 20th century such as Milwaukee(Blount et al., 1958; Lonstein & Winter, 1994), Boston(Emans et al., 1986; Périé et al., 2003), Chêneau(Hopf & Heine, 1985; Rigo & Weiss, 2008), Charleston(Lee et al., 2012) and Lyon brace(De Mauroy et al., 2008). These braces differ based on their rigidity, symmetry, openings (posterior/ interior), breathing technique and principle of correction(Grivas et al., 2018). Some braces are constructed to apply de-rotation and tractive force to the spine (Lonstein & Winter, 1994) or pure spine bending (Wiemann et al., 2014), while others are custom-made to provide three-point pressure bending along with de-rotation on abnormal spine curves and apices (Park et al., 2018; Rigo & Weiss, 2008).

Although braces are quite effective in limiting the curve progression or even correcting the cobb angle. However, their passive, rigid, and static designs limit the motion of the spine column. Results in stiffening of the spine and weakening of the muscles around it. Rigid braces affect cardiopulmonary efficiency and also cause skin breakdown and abnormal bone deformation. Therefore, designing a brace or spinal exoskeleton which allows the necessary movements and bring back the patient to correct posture is needed. That kind of dynamic brace can also be used as an assistive device after post-operative rehabilitation to stabilize the spine and keeping the spine in a correct posture.

Some soft braces such as Spinecor (Gutman et al., 2016; Wong et al., 2008), ScoliSMART (Morningstar, 2013) and Tria-C (Veldhuizen et al., 2002) have also been developed to enhance mobility and comfort, but they are passive and have no control

[a] https://orcid.org/0000-0002-5936-447X
[b] https://orcid.org/0000-0001-8236-522X
[c] https://orcid.org/0000-0002-5691-8115
[d] https://orcid.org/0000-0003-2962-2594

Ali, A., Fontanari, V., Fontana, M. and Schmölz, W.
Soft Active Dynamic Brace for Spinal Deformities.
DOI: 10.5220/0010343301690174
In *Proceedings of the 14th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2021) - Volume 1: BIODEVICES*, pages 169-174
ISBN: 978-989-758-490-9

over the amount of force being applied. The University of Colombia developed an active dynamic brace named ROSE(Murray et al., 2020; Park et al., 2018). It applies corrective forces at the different cross-sections of the torso while allowing the mobility. ROSE uses two-layer Stewart platform which is actuated using eight series actuators. These actuators increased the weight as well as the power consumption of the device. Braces are supposed to be worn over 18 hours a day which limits the use of ROSE dynamic brace.

This article presents the design of the novel soft active dynamic brace using twisted string actuation mechanism. This article focuses on the design requirements and modelling of twisted string actuator for the soft active dynamic brace to treat scoliosis. The objective of the research is to develop a brace which can apply controlled forces and allow the movement of the spine to overcome the limitation of passive rigid braces.

2 ACTIVE DYNAMIC BRACE

The active dynamic brace is a soft brace developed to treat spine deformities and enhance the comfort and mobility of the spine. The brace uses a compact lightweight actuation mechanism to apply corrective forces to the spine. Following sections explain the brace working principle, design and actuation mechanism etc.

2.1 Working of Brace

The active dynamic brace uses elastic resistance to generate corrective movement of the spine with the movement of the patient. In the long term, this will reprogram the neuromuscular system and will be able to slow or stop the curve progression and improve the overall posture of the patient. Elastic resistance levels are being controlled using a compact low powered actuation mechanism which results in controlled corrective forces being applied to torso.

The objective of the brace is to improve the spinal alignment and pain relief by offloading the muscles, nerve roots and joints of the spine. It will stabilize the spine by reinstructing the movement patterns while keeping the spine in the correct (de-rotated) posture. Steady correction in spinal and postural alignment will help to obviate the typical deterioration of posture and progression of spinal degeneration disease.

Active dynamic brace treatment will provide in pain relief and help in the postural correction in adolescences. It will prevent the progression of cobb angle in adults with scoliosis and other spinal deformities like kyphosis. It will provide effective control over scoliosis while preserving the near-normal movement. It will reduce the risk of muscle atrophy observed in rigid braces. The dynamic active brace will be able to provide specific localized control of the spine and body posture, combined with curve specific corrective movements.

Figure 1: Dynamic Active Soft Brace.

2.2 Brace Design

In the proposed design shown in Figure 1, the corrective bands are attached to a contoured body vest which covers the end of the rib cage. It consists of four 50 mm wide elastic bands which provide thoracic rotation, shoulder rotation and left lateral flexion. Firstly, the right thoracic flap (orange band) is attached to the lower right corner of the vest and wrap around the rib cage to finally attach to the pelvic back of the body. This band provides thoracic rotation in a counterclockwise direction and attached using velcro crocodile strips. The tension in the band can be adjusted to keep the spine at the correct posture. The second flap (Tosca green band) is attached to the left thoracic base. This flap wraps around the abdominal part of the body and goes all the way to the right half of pelvic back. Tension in this band is adjusted bit less as compared to the orange flap to keep the spine rotated in a counterclockwise direction. Third band (purple flap) attached to the left shoulder, rotates around the rib cage and back and finally attached in the front of the pelvic belt. This band generates clockwise shoulder rotation and left lateral flexion at T12. The fourth band, the right shoulder flap generates clockwise shoulder rotation and clockwise shoulder tilt.

The tensions in the elastic bands are being controlled using twisted string actuators. A Twisted String Actuator (TSA) is a simple, cheap, portable and compact mechanism and is an alternative to conventional gear systems. In the TSA, a string that is co-axially attached to the motor shaft acts as a high-ratio gear, which yields the potential to generate high output force with low input torque.

2.3 Actuation Mechanism

The dynamic active soft brace uses twisted string actuators as an actuation mechanism. Actuation module consists of Pololu Brushed DC gear motor 2386 with gear ratio 150:1, equipped with optical encoders. DC gear motor shaft is attached to the 3mm four-hole mounting hub, which twists the four Dyneema fishing strings as shown in Figure 2. Actuation module for a single TSA weighs approximately 150 grams. Resulting in total device weight nearly 1Kg including power. Which is significantly less than the other braces. When a string is attached to the motor and twisted it behaves like a gear with non-linear transmission ratio. Table 1 describes the parameters of the twisted string actuator.

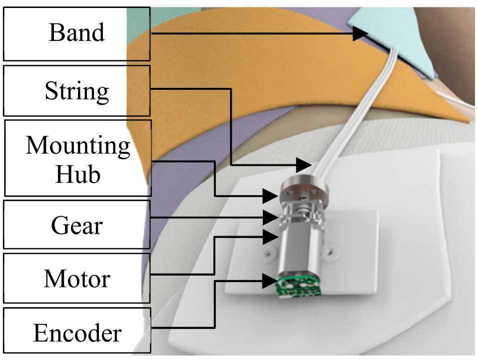

Figure 2: Twisted String Actuator.

Table 1: TSA parameters.

Parameter	Value
String Length (L_o)	200mm
String Radius (r)	0.725mm
Spring Constant of the band (K)	133 N/m
String Material	Dyneema
Motor Output Power	1.2 Watt
Output power at max efficiency	0.68 W
No load Current	70 mA
Current at max efficiency	0.31 A

2.4 Device Actuation Modelling

To effectively control the twisted string actuation mechanism, it is important to estimate the contraction of the string length based on the rotation of the actuator shaft. The shaft rotation θ can be measured through optical encoder attached to the motor. A conventional twisted string model can be derived from the string's helix geometry as shown in Figure 3 (Igor et al., 2021). The contraction of length X as a function of twist angle θ as shown in Figure 3 can be written as:

$$r^2\theta^2 + (L_0 - X)^2 - L^2 = 0 \tag{1}$$

$$X = L_0 - \sqrt{L_0^2 - r^2\theta^2} \tag{2}$$

Where L_o is the original length of the string bundle before twisting and r is the radius of string bundle after 5 turns. According to the conventional mathematical model of the TSA, a string of length L_0 twisted by a motor for an angle θ contracts by X amount.

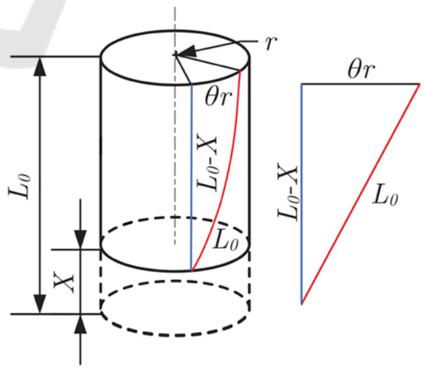

Figure 3: Schematic depiction of a section of a twisted string.

2.5 Experimental Evaluation

To verify the actuation model of the brace, a setup was designed consisting of Pololu DC gear motor

2386 with optical encoder and a gear ratio of 150:1 to twist the four 0.4mm Dyneema fishing strings of 20 cm (200mm) attached to the motor shaft and elastic band. A laser displacement sensor (keyence lk-g152) and a load cell were used to measure the actual position and pulling force of the string. The setup configuration can be seen in Figure 4. The string length contraction and the elastic resistance force graphs can be seen in Figure 5 and Figure 6.

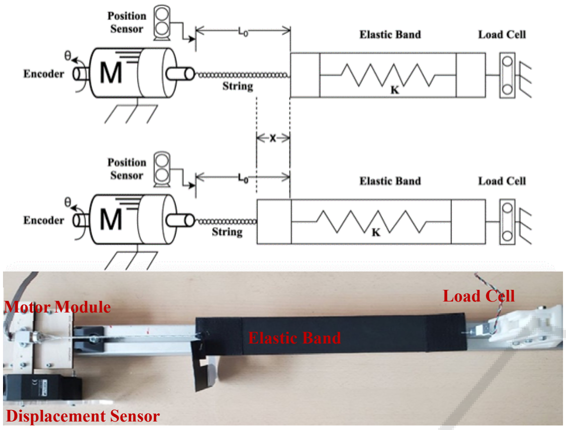

Figure 4: Actuation model verification setup.

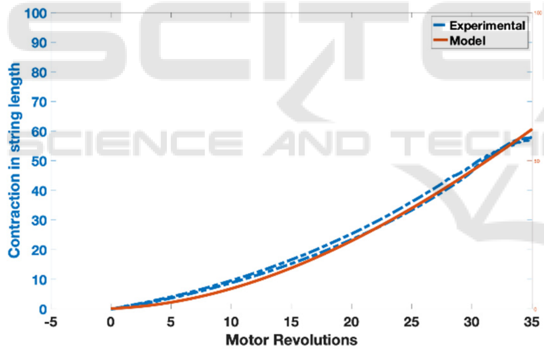

Figure 5: String length contraction with shaft revolutions.

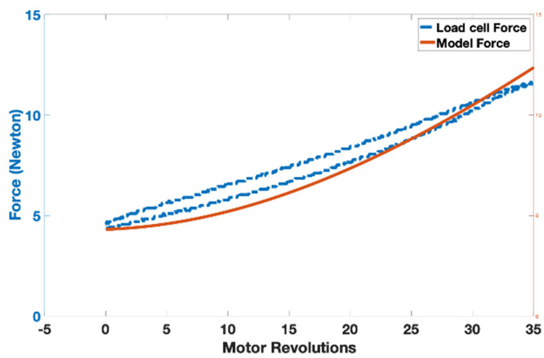

Figure 6: Force to control elastic resistance with respect to the shaft rotation.

The model tracks the position effectively with the RMSE of 0.17386 cm (1.7386mm). While the force model shows the RMSE of 0.7242 N.

2.6 Life Cycle

Evaluating the life cycle of the string is one of the important aspects of twisted string actuator. This study evaluates the life cycle of the twisted string actuator in different twisting regions. In the experiment, the effect of the number of motor shaft rotations per cycle on string behaviour is studied. The cycle represents the twisting of the string for a specific number of turns (20,30,35,45) and then it's untwisting back to the original position.

The experimental setup consists of the DC gear motor with an optical encoder attached to it, a current sensor that measures the system current and motor torque to report the system failure. A controller is programmed to conduct the cycles. A short delay of a few seconds is introduced after each cycle to reduce the motor temperature. The data of the number of turns and motor current is logged in the file with the duration equals the experiment time. Thus, having a record of the number of cycles of twisting that motor endured by analysing the system failure point through motor current.

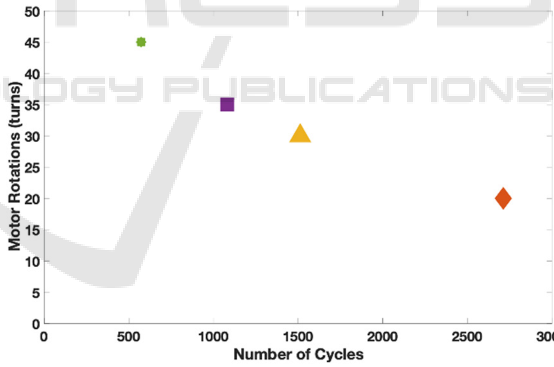

Figure 7: Life cycle test for twisted string actuator.

Region up to 20turns represents the low contraction region and have a higher life cycle of 2712. While the 35 turns cycle corresponds to the starting of the overtwisting phase and represents the maximum contraction limit without over twisting the string with a cycle life of 1080. The 45 turns are the limit where overtwisting is possible without untwisting issues. It can be seen from Figure 7 that the life cycles of the TSA reduce while going for the high contraction of the string. Therefore, the active dynamic brace operates below the overtwisting zone.

3 CONCLUSIONS

The dynamic active brace will preserve mobility and effectively correct or stabilize the curve progression. It will improve posture and body aesthetics. The dynamic active brace will not cause muscle atrophy as it will strengthen the muscles around the spine, providing lasting results after the treatment.

The dynamic active brace will have certain advantages over the rigid conventional braces. The elastic nature of the bands will allow the greater mobility and it will increase the physiotherapy performance. It will be able to solve the issues of stiffening of the spine and flat back problems. It has a compact, light design and can be wearable under the clothes, hence solving the socio implications. Modular design and cheap motor mechanism of the device solves the economic implications as well.

Rigid braces are not effective for obese patients. In contrast to rigid braces, the dynamic active brace can be a practical solution for obese patients as the extra weight will not restrain the dynamic action of the elastic flaps.

4 FUTURE WORK

In future, the focus of the research will be on the validation of the device. The interface pressure between the body and the elastic bands needs to be measured using a body measurement system by Tekscan® or similar. This will help to evaluate the relation between the tension in bands and the amount of force it is applying on the torso. The muscle activation also needs to be measured using electromyography sensor to validate the mobility of the spinal muscles in comparison to the rigid brace. There is a lot of potential in the improvement of twisted string actuation technology such as working on self-sensing supercoiled polymer twisted string actuation strings (Zhang et al., 2020). The advance stretch(Vu et al., 2019) to evaluate the motion of the spine and the tactile(Sferrazza et al., 2019) sensors can be embedded with elastic band to measure the stretch in the bands which will be help full to measure the six-dimensional stiffness of the torso. After the validation of device, the goal is to go for the clinical trials of the device.

ACKNOWLEDGEMENTS

This project has received funding from the Italian Ministry for Education, University, and Research (MIUR) through the "Departments of Excellence" program.

REFERENCES

Blount, W. P., Schmidt, A. C., KEEVER, E. D., & Leonard, E. T. (1958). The Milwaukee brace in the operative treatment of scoliosis. *JBJS*, *40*(3), 511–525.

De Mauroy, J. C., Lecante, C., Barral, F., Daureu, D., Gualerzi, S., & Gagliano, R. (2008). The Lyon brace. *Disability and Rehabilitation: Assistive Technology*. https://doi.org/10.1080/17483100801904069

Emans, J. B., Kaelin, A., Bancel, P., Hall, J. E., & Miller, M. E. (1986). The boston bracing system for idiopathic scoliosis: Follow-up results in 295 patients. *Spine*. https://doi.org/10.1097/00007632-198610000-00009

Grivas, T. B., de Mauroy, J. C., Wood, G., Rigo, M., Hresko, M. T., Kotwicki, T., & Negrini, S. (2018). Brace classification study group (BCSG): part one-definitions and atlas (Retraction of Vol 11, art no 43, 2016). *Scoliosis and Spinal Disorders*, *13*.

Gutman, G., Benoit, M., Joncas, J., Beauséjour, M., Barchi, S., Labelle, H., Parent, S., & Mac-Thiong, J. M. (2016). The effectiveness of the SpineCor brace for the conservative treatment of adolescent idiopathic scoliosis. Comparison with the Boston brace. *Spine Journal*. https://doi.org/10.1016/j.spinee.2016.01.020

Hopf, C., & Heine, J. (1985). Long-term results of the conservative treatment of scoliosis using the Cheneau brace. *Zeitschrift Fur Orthopadie Und Ihre Grenzgebiete*, *123*(3), 312–322.

Igor, G., Ryu, J. H., & Nedelchev, S. (2021). *Twisted String Actuation Systems: Applications, Modelling, and Control*. Elsevier Science. https://books.google.it/books?id=MwttxAEACAAJ

Lee, C. S., Hwang, C. J., Kim, D. J., Kim, J. H., Kim, Y. T., Lee, M. Y., Yoon, S. J., & Lee, D. H. (2012). Effectiveness of the Charleston night-time bending brace in the treatment of adolescent idiopathic scoliosis. *Journal of Pediatric Orthopaedics*. https://doi.org/10.1097/BPO.0b013e3182561193

Lonstein, J. E., & Winter, R. B. (1994). The Milwaukee brace for the treatment of adolescent idiopathic scoliosis. A review of one thousand and twenty patients. *Journal of Bone and Joint Surgery - Series A*. https://doi.org/10.2106/00004623-199408000-00011

Morningstar, M. (2013). Outcome observations in patients using a scoliosis activity suit: a retrospective chart review after one-year follow-up. *J Scoliosis Rehabil*, *2013*, 1–10. https://www.treatingscoliosis.com/images/research/2013-1291_suit.pdf

Murray, R. C., Ophaswongse, C., Park, J. H., & Agrawal, S. K. (2020). Characterizing Torso Stiffness in Female Adolescents with and without Scoliosis. *IEEE Robotics and Automation Letters*. https://doi.org/10.1109/LRA.2020.2969945

Ogilvie, J. (2010). Adolescent idiopathic scoliosis and genetic testing. In *Current Opinion in Pediatrics*.

https://doi.org/10.1097/MOP.0b013e32833419ac

Park, J. H., Stegall, P. R., Roye, D. P., & Agrawal, S. K. (2018). Robotic Spine Exoskeleton (RoSE): Characterizing the 3-d stiffness of the human torso in the treatment of spine deformity. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. https://doi.org/10.1109/TNSRE.2018.2821652

Périé, D., Aubin, C. E., Petit, Y., Beauséjour, M., Dansereau, J., & Labelle, H. (2003). Boston brace correction in idiopathic scoliosis: A biomechanical study. *Spine*. https://doi.org/10.1097/00007632-200308010-00008

Rigo, M., & Weiss, H. R. (2008). The Chêneau concept of bracing--biomechanical aspects. *Studies in Health Technology and Informatics*.

Sferrazza, C., Wahlsten, A., Trueeb, C., & D'Andrea, R. (2019). Ground Truth Force Distribution for Learning-Based Tactile Sensing: A Finite Element Approach. *IEEE Access*. https://doi.org/10.1109/ACCESS.2019.2956882

Veldhuizen, A. G., Cheung, J., Bulthuis, G. J., & Nijenbanning, G. (2002). A new orthotic device in the non-operative treatment of idiopathic scoliosis. *Medical Engineering and Physics*. https://doi.org/10.1016/S1350-4533(02)00008-5

Vu, L. Q., Amick, R. Z., Kim, K. H., & Rajulu, S. L. (2019). Evaluation of lumbar motion with fabric strain sensors: A pilot study. *International Journal of Industrial Ergonomics*. https://doi.org/10.1016/j.ergon.2018.11.007

Wiemann, J. M., Shah, S. A., & Price, C. T. (2014). Nighttime bracing versus observation for early adolescent idiopathic scoliosis. *Journal of Pediatric Orthopaedics*. https://doi.org/10.1097/BPO.0000000000000221

Wong, M. S., Cheng, J. C. Y., Lam, T. P., Ng, B. K. W., Sin, S. W., Lee-Shum, S. L. F., Chow, D. H. K., & Tam, S. Y. P. (2008). The effect of rigid versus flexible spinal orthosis on the clinical efficacy and acceptance of the patients with adolescent idiopathic scoliosis. *Spine*. https://doi.org/10.1097/BRS.0b013e31817329d9

Zaina, F., De Mauroy, J. C., Grivas, T., Hresko, M. T., Kotwizki, T., Maruyama, T., Price, N., Rigo, M., Stikeleather, L., Wynne, J., & Negrini, S. (2014). Bracing for scoliosis in 2014: State of the art. *European Journal of Physical and Rehabilitation Medicine*.

Zhang, J., Bombara, D., Fowzer, S., & Brennan, C. (2020). Compliant and Large-Strain Twisted String Actuators using Supercoiled Polymers. *2020 3rd IEEE International Conference on Soft Robotics, RoboSoft 2020*. https://doi.org/10.1109/RoboSoft48309.2020.9115985