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Estimating Spinal Position in 3D Using a Connected Garment to Assess Bracing Fit for Adolescent Idiopathic Scoliosis

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Abstract

Adolescent idiopathic scoliosis (AIS) is characterized by a three-dimensional curvature of the spine that affects a ratio of one boy to eight girls. Frequent monitoring of AIS is crucial due to unpredictable growth spurts. For eligible patients, bracing can be considered to prevent curve progression. This study aims to provide a 3D visualization of the patient's postural condition and bracing results, in real time. We propose a new custom designed connected garment for tracking and monitoring patient's posture. Since connected garments have proven to be a promising markerless motion capture method, a bodysuit was designed for this experiment. The simulation of the garment and fabric was created with CLO 3D 2024 simulation software. The prototype's main function is to quantify indicators of AIS deformities using stitch-based stretch sensors. The bodysuit transmits signals through a data acquisition system for precise and high-rate transmission. Simultaneously, a customized algorithm generates on a computer a 3D visualization of the posture using Processing 4 (2023). The experimental results are validated using inertial measurement units (IMU). Finally, the outcome of this research is a system for continuous monitoring of AIS, without an impact on daily life as it will have the same attributes as everyday wear.

Keywords: Adolescent idiopathic scoliosis bracing, Bracing monitoring, 3D Spinal estimation, Connected garment design, Textile sensors, Stitch-based sensors

1. Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional abnormal curvature and rotation of the spine [1]. AIS affects 2% to 3% of adolescents in the population, of which 89% are aged between 10 and 16 years [2]. The severity of AIS is evaluated using the Cobb angle, which measure the angle between the two most rotated vertebrae. A mild curvature has an angle below 10° [1]. The ratio between girls and boys remains the same for angles between 10° and 20°. For angles 20° inclusively, the proportion remains constant with a ratio of 1.3:1 [1]. It increases to 5.4:1 for an angle of 21° to 30° [1]. From 30° and above, the ratio becomes approximately 8:1 [3,1]. Monitoring of the curve progression is important in the management of AIS, especially during growth spurts. Bracing is routinely prescribed to prevent curve progression [4]. For AIS patients with brace, low-dose X-rays are used to monitor the evolution of the Cobb's angle, measured at a frequency of 3 to 6 months [5], making measurements of Cobb's angle, to evaluate the effect of bracing, less harmful for children with multiple follow-ups [6,7]. However, as of today, continuous monitoring of the curve progression is not feasible and there is a lack of data documenting the patient's posture inside the brace.

2. Purpose of the study

This study aims to provide the patient's postural condition and bracing results, in real time. This study has taken a user-centric approach while benefitting from having a multidisciplinary team to bridge a gap between garment design and engineering. We propose a new custom designed connected garment for tracking and monitoring patient's posture. Since connected garments have proven to be a promising markerless motion capture method, a bodysuit was designed for this experiment. A connected garment would be an easy and accessible tool for quantitative data collection of the evolution of AIS reducing intervals between follow-ups, hence improving healthcare and providing valuable, continuous data about progression factors of AIS.

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3. Related work

3.1. Assessment of bracing effectiveness in AIS

Bracing effectiveness is defined by quantity and quality, regarding the number of hours the brace is worn and its structure. The evaluation of effectiveness is carried out using data from the patient's compliance with the prescribed number of hours of wear and on the adjustment of the orthopedic device to meet the corrective needs of the patient's AIS [8]. For quantity assessment, [9] reports that the addition of temperature sensors, in the studies of [10] and [11] to detect the duration of wearing the corset, has a 98.5% reliability. The BRAIST trial [12], is a study that also uses a temperature recorder to demonstrate the positive correlation between the success of treatment and the duration of wearing the corset. However, they have discovered that 41% of patients in a group of participants required to wear braces received positive feedback despite not wearing it for the prescribed time. The indications and instructions lack guidelines and supervision [12] which brings to light the unresolved issue of unnecessary treatment for some patients [13], [14]. Fundamentally, quickly detecting patients at risk of rapid progression is key, as they can benefit the most from bracing treatment. As for quality assessment, studies by [8] and [15] have explored the addition of commercial pressure sensors to quantify both fit and wear time of bracing. In the research of [16], the strain/force limit exerted by the brace to evaluate its quality is established subjectively by the orthotist consulted for the study since no scientific literature has defined the optimal correction pressure that the brace must exert on the trunk. Furthermore, the research from [15] discovers that frequent wearing of the brace alleviated its stiffness by decreasing the strain by 33% after four weeks of bracing with a TLSO (thoraco-lumbar-sacral orthosis). This supports that, although compliance with wear time is respected by the patient, the orthosis's rigidity deforms/relaxes for better comfort but becomes unsuitable for curvature correction, its main functionality. Therefore, frequent follow-ups during bracing must be based on quantifiable data to tailor the treatment depending on the patient's specific needs. As a result, preventing unnecessary bracing or rapidly adjusting to an alarming progression of the curvature. Exploring other varieties of sensors than temperature and pressure sensors also their location whether inside the brace or elsewhere on the body would generate data diversity and in return contribute to an objective evaluation of the effectiveness of the treatment.

3.2. Connected Garment for Upper Body Posture Detection

Research on connected garment has contributed to advancing knowledge on detection of upper body posture. Strain sensors to detect deformation of the garment were attached on a customized catsuit and connected with conductive stitching to monitor upper body posture [17]. This study tested trunk and arm movements with 27 poses (15 sitting, 12 standing up) with 8 male participants. For postural rehabilitation monitoring, a prototype of a stretchable t-shirt equipped with an induction sensor located along the spine was tested with 4 participants with at least 2 male participants and 4 sitting positions [18]. A hand-stitch seam with a conductive thread makes it possible to detect the elongation of the garment according to the posture. Similarly, [19] designed three prototypes to demonstrate the feasibility of detecting spinal flexion and curvature with a sewed sensor. Sensors were applied to three styles of tops: a vest, a sleeveless and waist-length top, a t-shirt, a long-sleeved hip length top and a leotard, a fitted sleeveless jumpsuit. Ten participants which included 1 male took part in the trial and were instructed to perform 5 repetitions of standing upright then roll to the maximum their spine in the sagittal plane. The leotard obtains the best results to track motion and posture. On the other hand, the fabric of the jacket and t-shirt, having no restraint at the bottom of the garment, wrinkles during movement, which affects the shape of the sensors and thus the signals. Therefore, it is recommended to hold the garment at the crotch to give the garment an anchor. Finally, the first study used machine learning to classify each posture [17] while the others were validated with an optical monitoring system, 3 cameras Coda CX1, IR and markers [18], 3 reflective motion capture markers and a Vicon Nexus motion-capture system [19].

3.3. Textile substrate for stitch-based sensors

The choice of fabric, to host the sensors, relies on its main structure, weaving or knitting, and secondary structure such as single/double ribbed knit or knit jersey. Even with their difference in stretchability, both main structures can be used as a substrate [20]. Its composition also plays a defining role in the elasticity whether synthetic (ex. polyester or nylon) or natural (ex. cotton or hemp). It can be enhanced by blending fibres with elastic properties like spandex or elastomers. Fabric blends, with varying percentages of elastic fibre have been tested as a substrate: 95% cotton with 5% spandex blend [21], 90% polyester or nylon with 10% spandex [21], 75% nylon with 25% spandex [20]. Spandex has considerable properties, such as stretchability and elasticity to lower hysteresis of the fabric, the difference between stretching phases of a cycle (elongation and recovery) [20]. This quantifiable parameter evaluates the ability for the fabric to regain its original shape without showing permanent deformation. For normal joint movements, 35% to 45% elasticity is recommended and as for daily comfort when the fabric fits tight on the body without being uncomfortable, 25% to 30% is needed [22]. It is essential to maintain the stability of the fabric by reducing/eliminating drift, the difference between the peaks of a cycle, and hysteresis. An ideal sensor substrate would be devoid of drift and hysteresis [20].

3.4. The importance of human-centric design for a connected garment

Apparel providing a continuous health monitoring solution must be worn for a long period of time. Consequently, it is essential to prioritize human factors regarding the impact of design choices on comfort as well as on the performance of the sensors [17,23]. The flexibility and extensibility of the sensors, having an impact on comfort [30], are other characteristics of which can improve the experience of wearing the garment and increase the willingness of users to use a monitoring tool [19]. Also, clothing is an ideal and omnipresent basis for the development of electronic applications simply because human beings have long worn and still wear clothes to cover themselves [25,26]. The ease of use and ubiquity of the garment are key elements for long-term clinical monitoring. Placing sensors as close as possible to the human body is an intuitive approach to sensor design [23]. A method promoting long-term wear while considering the user's comfort is the integration of the e-textile sensor into clothing for movement of pose detection. Although, wearing tight-fitting clothing can be socially awkward or physically inconvenient, it is essential to offer a minimally invasive garment while respecting the physical and social comfort of the user [26]. In addition, the aesthetic aspect of the garment must also be considered by integrating discrete sensors, because the users, over complex and insecurity, have an attachment to the way they present themselves through their fashion choices [26].

4. Methods

4.1. Test protocol for tension and elongation of elastic fabric

The elastic properties of the substrate fabric for the garment not only ensure comfort for the wearer but also ensure its durability. The test protocol for the garment fabric was based on the ASTM D4964-96(2020) Standard test method for tension and elongation of elastic fabrics [27]. A substrate sample was fabricated measuring 100 by 150 mm (± 0.5 mm), having the grainline (ribs) in the same direction as the width of the sample. The conditioned sample, at 22.0° and 47.8% relative humidity, was sown with an industrial overlock sewing machine (JUKI MO-2316 2 needles, 4 threads) with 2 stretch assembly stitches (ISO #514) to attach and loop the sample. A seam value of 5 mm (± 0.5 mm) was added for the assembly. With an MTS Alliance RF/200 (MTS Systems Corporation, Eden Prairie, MN, USA) traction machine and their TWElite 4.3.0.352 software [28], 5 cycles for each of the three elongation percentages, 30%, 50% and 70%, were programmed with a speed of 90 mm/min, a force factor of 50 N/V, a displacement factor of 10 mm/V and 55 N, no load cell was required as the weight of the anvil was enough. The setup is demonstrated in the Fig. 1. where the looped sample was retained by a rod inserted on the side of the anvil. The data collected is the strain (N) applied by the traction machine and elongation (mm) of the sample.

Fig. 1 Setup of the elongation testing of the substrate fabric with the MTS Alliance RF/200 traction apparatus.

4.2. Design of the connected garment prototype

The proposed connected garment was designed using CLO3D (CLO, Virtual Fashion LLC, Seoul, South Korea) [29]. CLO3D is a cloud-based fashion design software that allows virtual creation of a garment prototype and simulation of poses for visual examination of scoliosis (Fig. 3). The software offers several anthropometric models of young person ranging from newborns to adults with different gender, male or female. Designs in 3D with fabric can simultaneously be converted in 2D patterns, saving hours of manual patternmaking. We took advantage of the visual 3D sampling simulator to create multiple iterations from which we gained feedback within the team and with healthcare professionals. A simulation of the garment and fabric was created with CLO 3D 2024 simulation software (Fig. 2. a). The prototype's main function is to quantify indicators of AIS deformities using stitch-based stretch sensors (Fig. 2. b and c). This simulation was used as a starting point.

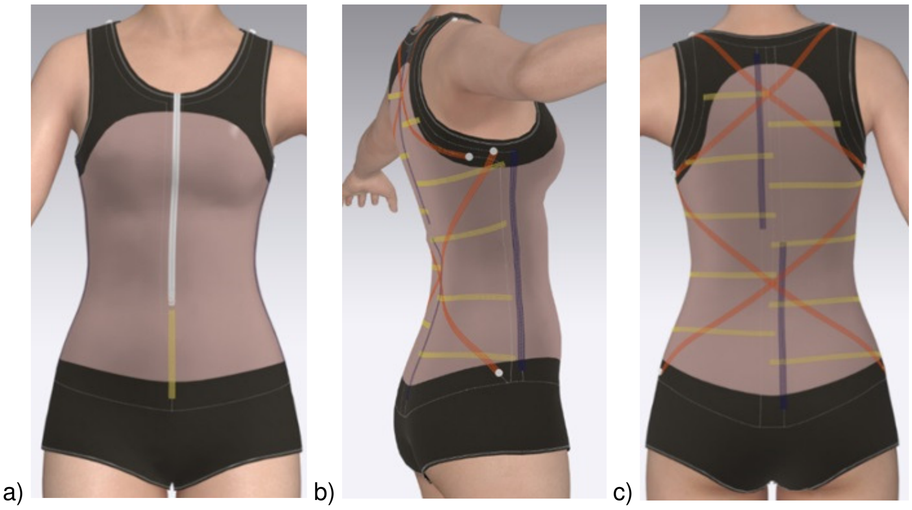

Fig. 2. Simulation of the design of a bodysuit with stitch-based sensors (CLO 3D 2024) a) Front view b) Lateral view with sensors c) Back view with sensors

6. Analysis & Results

6.1. Mechanical testing for tension and elongation of elastic fabric

The data acquisition generated data at a frequency of 100 Hz. Consequently, down sampling was essential to visualize the drift and hysteresis of the substrate fabric. The drift indicates irregularity between the maximum values of peaks or the minimum value of depth. It also quantifies and ensures uniformity and repeatability of the response from the sensor. The perfect substrate for the sensor would have peaks completely aligned and at the same height and depth. It is explained by a permanent or semi-permanent deformation of the substrate after several cycles of elongation and recuperation.

Discrepancy in the 30% elongation graph (Fig. 3. a), where the load value dips at - 4.204 N, seems to be an isolated event as the 50% and 70% elongation cycles were done consecutively and did not show similar behaviour. The setup might have replaced itself for the second and following cycles. As for the heights of the peaks, the 30% elongation graph demonstrates minimal drift. While the first cycle in the 50% elongation graph shows a slightly higher peak (Fig. 3. b) and a noticeable irregularity from the 70% elongation graph (Fig. 3. c).

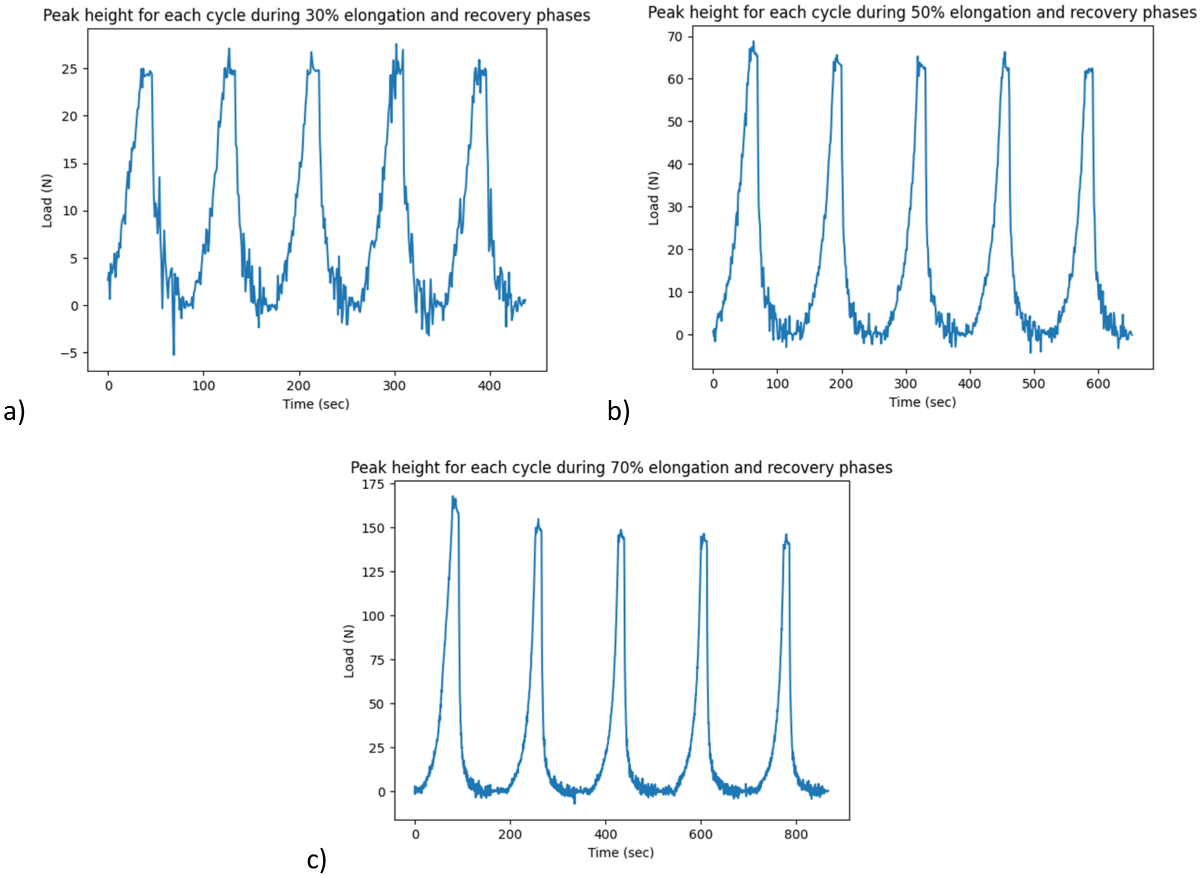

Fig. 3. Graphs showing peak height for each elongation-recovery cycle
a) 30% b) 50% c) 70%.

The following graphs (Fig. 4.) of the strain sustain by the fabric were generated by superimposing all 5 cycles of elongation and recovery phase at 0 mm of elongation. These graphs show the hysteresis of the fabric where the ideal substrate would have all cycles perfectly aligned. Again, aside from the first cycle, more apparent in Fig.4 b and c with 50% ad 70% elongation, the deformation stabilizes during the following cycles. Monitoring posture does not require the same working range as joint movements and 50% of elongation will suffice to detect asymmetry from the trunk.

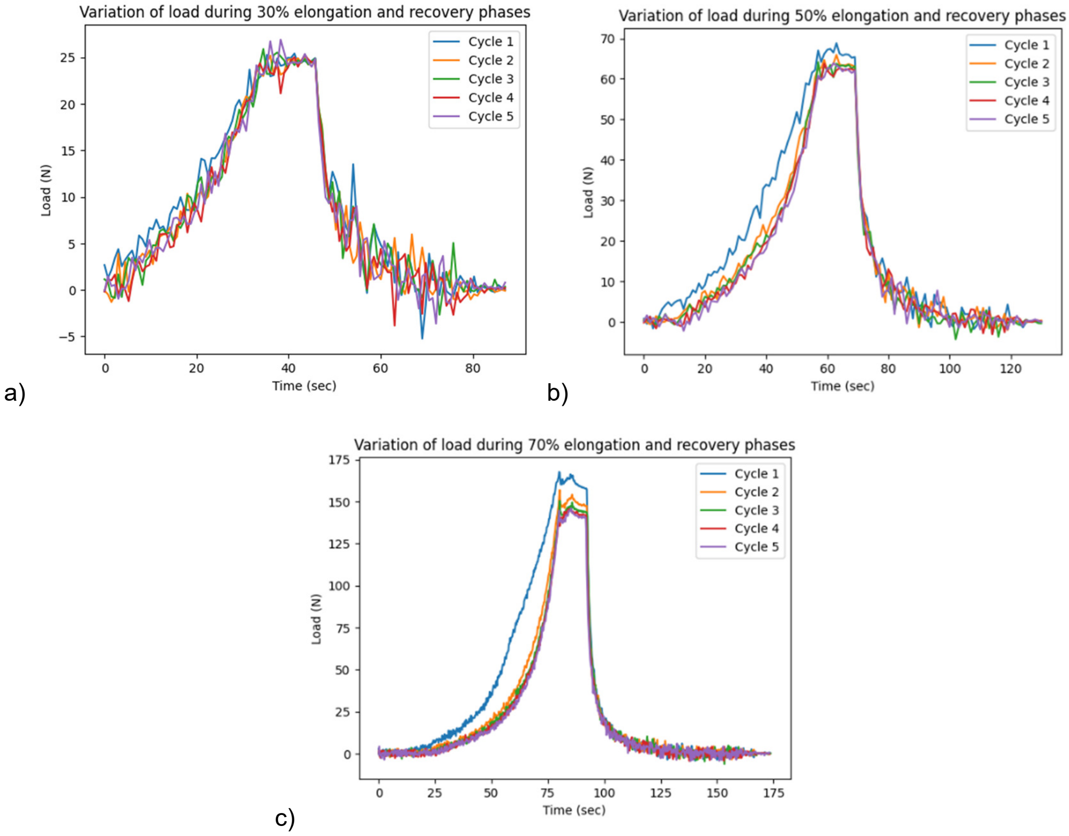

Fig. 4. Graphs of the load sustained by the samples for each elongation percentage a) 30% b) 50% c) 70%.

6.2. Prototype of the connected garment

As a human-centric study, adaptation of the prototype to a different age group was considered. The design has transitioned from an adult bodysuit more in the likes of a bathing suit to a body with shorts to be suitable for kids, specifically adolescents from ages 10 to 16. The new design is unisex, and the fabric allows for comfort and body shape diversity. The garment is made of a single substrate, stretchable in 4 ways with properties modified by adding a fusible knit interfacing strategically placed as anchors for sensors and the garment, at shoulder levels and at the crotch. The interfacing completely removes the stretchability of the substrate vertically and reduces the stretchability horizontally as to tighten the garment in the selected areas (Fig 5. a and b). For this reason, the design of the crotch area of the bodysuit was revised to keep its full extensibility and accommodate both sexes. Finally, a collar was added to the garment giving the possibility for the sensor to reach the cervical vertebrae (C7). The automatic generation of a printable pattern (Fig 5. c) enables the validation of our new design with a sown garment. The fabric chosen is a ribbed 1x1 knit made of 95% cotton and 5% spandex (Montloup Inc., Montreal, Qc, Canada) [30]. It is locally knitted and sourced. The cotton is organic which makes the garment hypoallergenic, lightweight and soft.

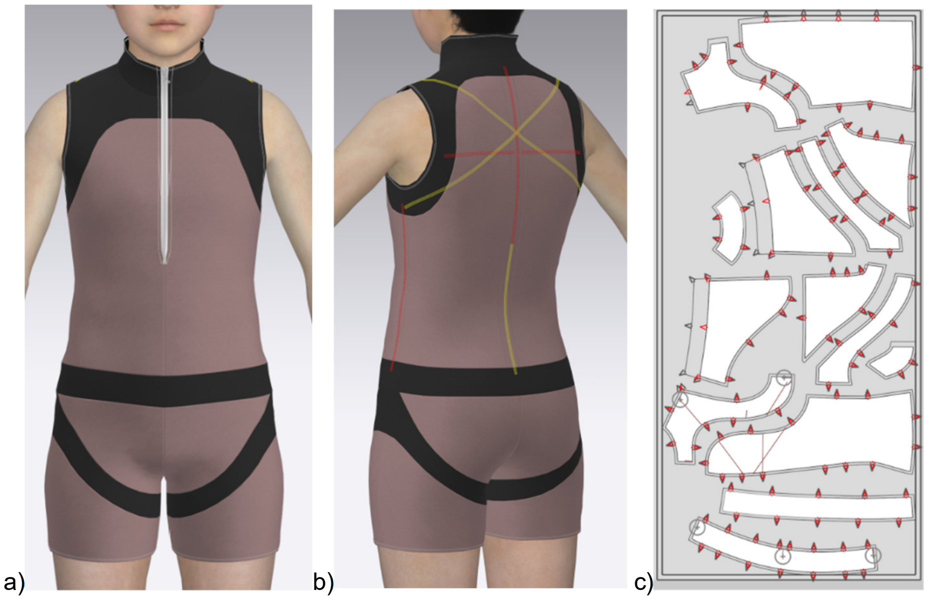

*Fig. 5. Design of the prototype and pattern with CLO3D after feedbacks from healthcare professionnals
a) Front view b) Side and back view with sensors c) Printable pattern of the garment*

As a feature to a testing protocol with participants, simulating different poses needed to collect data adds an easy way, especially for children, to comprehend the task that will be required from them and choose with better comprehension and judgment to opt for an experiment or not. In Fig. 6., an avatar of a 10 year old girl simulates the Adam's forward bending test commonly used during visual evaluation of scoliosis. This method doesn't require anyone to be photographed or filmed while reenacting the experimental protocol.

*Fig. 6. Simulation of the Adam's forward bending test posture
with the avatar's joint feature from CLO3D.*

6.3. Application simulation

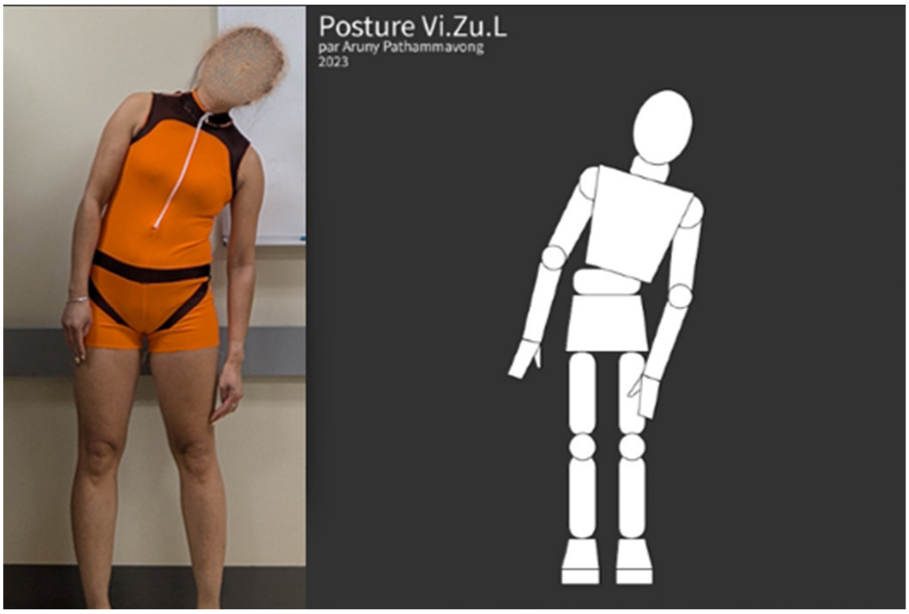

Fig. 7. Posture visual application using Processing 4 and prototype of the connected garment.

A visualization system was developed to translate sensor signals from a garment into a visualization of the posture on a computer with Processing 4 [31], an open-sourced visual arts software. It shows a human silhouette with the upper body moving in real time while receiving signals from the sensors, thus mimicking the posture of the user wearing the connected garment in real time. The experimental results are validated against inertial measurement units (IMU) (Movella Dot, USA) sensors [32].

7. Conclusions

This study presents a connected garment approach for the monitoring of AIS patients. Part of the process of designing a connected garment is knowing who it is meant for and taking an innovating approach with compassion and empathy for AIS patients. The task of integrating a novel textile-based sensor to a garment has been a challenge for many studies. We chose to design our own garment and with an iterative approach pinpointing constraints regarding the context of our research but also the advantages of having flexibility for the textile sensor system. The design of the garment and the study should take diversity of gender and morphology into account as it is necessary to test the ability/performance of the connected garment to recognize different levels of curvatures no matter the shape or size of the user. This approach will first be validated using healthy participants and further testing with AIS patients between the age of 10 to 16 is needed to obtain more conclusive results. A unisex design in multiple sizes will accommodate the needs for this specific cohort. The design was adjusted to an age-appropriate garment and to reduce wrinkles in the tight fitted garment during movements yet not compromising the user's comfort. Finally, the outcome of this research might lead to a system for continuous monitoring of AIS patients, without an impact on daily life as it will have the same attributes as everyday wear.

References

[1] S. Negrini *et al.*, "2016 SOSORT guidelines: orthopaedic and rehabilitation treatment of idiopathic scoliosis during growth," *Scoliosis*, vol. 13, no. 1, p. 3, Dec. 2018, https://doi.org/10.1186/s13013-017-0145-8.

[2] A. M. Zaydman *et al.*, "Etiopathogenesis of adolescent idiopathic scoliosis: Review of the literature and new epigenetic hypothesis on altered neural crest cells migration in early embryogenesis as the key event," *Medical Hypotheses*, vol. 151, p. 110585, Jun. 2021, https://doi.org/10.1016/j.mehy.2021.110585.

[3] J. A. Janicki and B. Alman, “Scoliosis: Review of diagnosis and treatment,” *Paediatrics & Child Health*, vol. 12, no. 9, pp. 771–776, Nov. 2007, https://doi.org/10.1093/pch/12.9.771.

[4] D. Addai, J. Zarkos, and A. J. Bowey, “Current concepts in the diagnosis and management of adolescent idiopathic scoliosis,” *Childs Nerv Syst*, vol. 36, no. 6, pp. 1111–1119, Jun. 2020, https://doi.org/10.1007/s00381-020-04608-4.

[5] S. Negrini *et al.*, “2011 SOSORT guidelines: Orthopaedic and Rehabilitation treatment of idiopathic scoliosis during growth,” *Scoliosis*, vol. 7, no. 1, p. 3, Jan. 2012, https://doi.org/10.1186/1748-7161-7-3.

[6] A. Bagheri, X.-C. Liu, C. Tassone, J. Thometz, and S. Tarima, “Reliability of Three-Dimensional Spinal Modeling of Patients With Idiopathic Scoliosis Using EOS System,” *Spine Deformity*, vol. 6, no. 3, pp. 207–212, May 2018, https://doi.org/10.1016/j.jspd.2017.09.055.

[7] L. Lau *et al.*, “Sequential spine-hand radiography for assessing skeletal maturity with low radiation EOS imaging system for bracing treatment recommendation in adolescent idiopathic scoliosis: A feasibility and validity study,” *Journal of Children’s Orthopaedics*, vol. 13, pp. 1–8, Aug. 2019, https://doi.org/10.1302/1863-2548.13.190007.

[8] E. Lou, D. Hill, D. Hedden, J. Mahood, M. Moreau, and J. Raso, “An objective measurement of brace usage for the treatment of adolescent idiopathic scoliosis,” *Medical Engineering & Physics*, vol. 33, no. 3, pp. 290–294, Apr. 2011, https://doi.org/10.1016/j.medengphy.2010.10.016.

[9] C. Cordani *et al.*, “Influence of Specific Interventions on Bracing Compliance in Adolescents with Idiopathic Scoliosis—A Systematic Review of Papers Including Sensors’ Monitoring,” *Sensors*, vol. 23, no. 17, Art. no. 17, Jan. 2023, https://doi.org/10.3390/s23177660.

[10] B. M. Benish, K. J. Smith, and M. H. Schwartz, “Validation of a Miniature Thermochron for Monitoring Thoracolumbosacral Orthosis Wear Time,” *Spine*, vol. 37, no. 4, p. 309, Feb. 2012, https://doi.org/10.1097/BRS.0b013e31821e1488.

[11] M. Takemitsu, J. R. Bowen, T. Rahman, J. J. Glutting, and C. B. Scott, “Compliance Monitoring of Brace Treatment for Patients with Idiopathic Scoliosis,” *Spine*, vol. 29, no. 18, p. 2070, Sep. 2004, https://doi.org/10.1097/01.brs.0000138280.43663.7b.

[12] S. L. Weinstein, L. A. Dolan, J. G. Wright, and M. B. Dobbs, “Effects of Bracing in Adolescents with Idiopathic Scoliosis,” *New England Journal of Medicine*, vol. 369, no. 16, pp. 1512–1521, 2013, https://doi.org/10.1056/NEJMoa1307337.

[13] A. J. Danielsson, R. Hasserius, A. Ohlin, and A. L. Nachemson, “A Prospective Study of Brace Treatment Versus Observation Alone in Adolescent Idiopathic Scoliosis: A Follow-up Mean of 16 Years After Maturity,” *Spine*, vol. 32, no. 20, p. 2198, Sep. 2007, https://doi.org/10.1097/BRS.0b013e31814b851f.

[14] J. O. Sanders, P. O. Newton, R. H. Browne, and A. J. Herring, “Bracing in Adolescent Idiopathic Scoliosis, Surrogate Outcomes, and the Number Needed to Treat,” *Journal of Pediatric Orthopaedics*, vol. 32, p. S153, Sep. 2012, https://doi.org/10.1097/BPO.0b013e31825199e5.

[15] O. Dehzangi, B. A. Bache, O. Iftikhar, J. Wensman, and Y. Li, “A smart point-of-care compliance monitoring solution for brace treatment of adolescent idiopathic scoliosis patients,” *Smart Health*, vol. 21, p. 100179, Jul. 2021, https://doi.org/10.1016/j.smhl.2021.100179.

[16] E. H. M. Lou, D. L. Hill, J. V. Raso, M. Moreau, and D. Hedden, “How quantity and quality of brace wear affect the brace treatment outcomes for AIS,” *Eur Spine J*, vol. 25, no. 2, pp. 495–499, Feb. 2016, https://doi.org/10.1007/s00586-015-4233-2.

[17] C. Mattmann, O. Amft, H. Harms, G. Troster, and F. Clemens, “Recognizing Upper Body Postures using Textile Strain Sensors,” in *2007 11th IEEE International Symposium on Wearable Computers*, Oct. 2007, pp. 29–36. https://doi.org/10.1109/ISWC.2007.4373773.

[18] E. Sardini, M. Serpelloni, and V. Pasqui, “Wireless Wearable T-Shirt for Posture Monitoring During Rehabilitation Exercises,” *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 2, pp. 439–448, Feb. 2015, https://doi.org/10.1109/TIM.2014.2343411.

[19] G. Gioberto, C. Compton, and L. E. Dunne, “Machine-Stitched E-textile Stretch Sensors,” *Sensors & Transducers*, vol. 202, no. 7, pp. 25–37, Jun. 2016.

[20] O. Tangsirinaruenart and G. Stylios, “A Novel Textile Stitch-Based Strain Sensor for Wearable End Users,” *Materials*, vol. 12, no. 9, Art. no. 9, Jan. 2019, https://doi.org/10.3390/ma12091469.

[21] B. Greenspan, M. L. Hall, H. Cao, and M. A. Lobo, “Development and testing of a stitched stretch sensor with the potential to measure human movement,” *The Journal of The Textile Institute*, vol. 109, no. 11, pp. 1493–1500, Nov. 2018, https://doi.org/10.1080/00405000.2018.1432189.

[22] Gibbs, P. & Asada, H. H., “Wearable Conductive Fiber Sensor Arrays for Measuring Multi-Axis Joint Motion,” presented at the 26th Annual International Conference of the IEEE EMBS, San Francisco, CA, USA, Sep. 2004. https://doi.org/10.1109/IEMBS.2004.1404316.

[23] G. Cesarelli, L. Donisi, A. Coccia, F. Amitrano, G. D’Addio, and C. Ricciardi, “The E-Textile for Biomedical Applications: A Systematic Review of Literature,” *Diagnostics*, vol. 11, no. 12, Art. no. 12, Dec. 2021, https://doi.org/10.3390/diagnostics11122263.

[24] A. Pandiyan *et al.*, “A comprehensive review on perovskite and its functional composites in smart textiles: Progress, challenges, opportunities, and future directions,” *Progress in Materials Science*, vol. 140, p. 101206, Dec. 2023, https://doi.org/10.1016/j.pmatsci.2023.101206.

[25] Martínez-Estrada, M., Gil, I. & Fernández-García, R., “An Alternative Method to Develop Embroidery Textile Strain Sensors,” *Sensors*, vol. 21, no. 949, Jan. 2021, https://doi.org/10.3390/textiles1030026.

[26] G. Gioberto and L. E. Dunne, “Garment-Integrated Bend Sensor,” *Electronics*, vol. 3, no. 4, Art. no. 4, Dec. 2014, https://doi.org/10.3390/electronics3040564.

[27] ASTM International, “Standard Test Method for Tension and Elongation of Elastic Fabrics.” Accessed: Jun. 23, 2024. [Online]. Available: https://compass.astm.org/document/?contentCode=ASTM%7CD4964-96R20%7Cen-US&proxycl=https%3A%2F%2Fsecure.astm.org&fromLogin=true.

[28] “MTS,” MTS. Accessed: Sep. 06, 2024. [Online]. Available: https://www.mts.com/en/products/software-monitoring/www.mts.com.

[29] “CLO: Best Digital Fashion Design Software,” CLO Official Site. Accessed: Aug. 29, 2024. [Online]. Available: https://www.clo3d.com.

[30] “Organic cotton spandex rib 1x1 11-11.5 oz,” Montloup. Accessed: Sep. 05, 2024. [Online]. Available: https://www.montloup.com/en/products/rib-1x1-cotton-organic-spandex-11-11-5-oz

[31] “Welcome to Processing!,” Processing. Accessed: Aug. 29, 2024. [Online]. Available: https://processing.org//.

[32] “Movella DOT | Movella.com.” Accessed: Sep. 05, 2024. [Online]. Available: https://www.movella.com/products/wearables/movella-dot.