Intelligent Environments 2024: Combined Proceedings of Workshops and Demos & Videos Session
M.J. Hornos et al. (Eds.)

doi:10.3233/AISE240017

Pervasive Monitoring System for Cervical Dystonia: A Feasibility Study Using 9DOF Sensors

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Abstract. Cervical dystonia, a neurological disorder characterized by involuntary muscle contractions in the neck, presents significant challenges in symptom monitoring due to its fluctuating nature. Current clinical assessments are limited by time constraints and infrequent patient visits. This paper presents the feasibility study of a novel approach to continuous symptom monitoring using a pervasive monitoring system equipped with 9DOF sensors. The system aims to capture the kinematic properties of head movement in patients with cervical dystonia, providing detailed data outside the clinical setting. We outline the development of this system, including the integration of sensors with a mobile application for real-time data logging. Our methodology involves a set of predefined movement protocols, established by practitioners, to standardize data collection. The system's performance is evaluated using both the sensor data and a reference system, OptiTrack, to ensure accuracy and reliability. Preliminary results confirm the viability of the proposed approach for tracking cervical-dystonia specific head movements.

Keywords. cervical dystonia, 9DOF sensors, pervasive monitoring

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1. Introduction

Cervical dystonia (CD), a distinct form of focal dystonia, presents with involuntary muscle contractions in the neck, leading to abnormal movements and postures of the head [1]. This movement disorder, while not widely prevalent [2], significantly impacts patients' quality of life [3]. The dynamic nature of CD symptoms, changing pattern [4], and intensity of movements, pose challenges for effective monitoring and treatment. Current clinical assessments [5], largely reliant on visual inspections and patient feedback during infrequent consultations, lack the granularity and consistency necessary for optimal management of the condition. In the pursuit of a more precise understanding of cervical dystonia, ongoing efforts focus on developing objective measurement tools that can accurately assess the severity and progression of this neurological disorder, paving the way for improved diagnostics and tailored therapeutic interventions [6,7,8,9].

1.1. Background and Related Work

Traditionally, Botulinum toxin injections are the primary treatment for CD [10,11], targeting specific muscles to alleviate symptoms. However, the selection of muscles for treatment is largely subjective, based on the clinician's experience and observation during the brief patient interaction. To address this challenge and enhance the precision of therapeutic interventions, recent efforts have delved into comprehensive analyses, such as the tables of abnormal head and neck postures labeling muscles involved in cervical dystonia [12,13]. These tables provide a valuable reference, offering a more systematic approach to muscle selection and contributing to the ongoing pursuit of refining and standardizing treatment protocols in cervical dystonia. This approach, while beneficial, is limited by its dependence on the unknown accuracy of these assessments and the inability to track symptom progression continuously.

The advent of wearable sensor technology offers a promising avenue for more objective and continuous monitoring of CD symptoms. Recent studies have employed various forms of wearable sensors, including inertial measurement units (IMUs), to capture the kinematic properties of movement disorders [14,15]. These technologies have shown potential in providing detailed insights into the movement patterns and anomalies associated with conditions like Parkinson's disease and essential tremor [16,17]. However, their application in the context of CD, particularly for at-home monitoring, remains under-explored.

In this light, our study introduces a novel application of the Movesens sensor, a type of 9DOF (Degrees of Freedom) sensor, to capture the intricate movements and postures associated with CD. This approach aligns with the growing interest in pervasive healthcare monitoring systems, where the focus is on integrating technology seamlessly into patients' daily lives for continuous health data collection.

This paper aims to bridge the gap in CD monitoring by presenting a feasibility study of the Movesens sensor system in accurately capturing head and neck movements specific for CD. By doing so, it contributes to the limited but growing body of knowledge on the use of sensor-based technologies in the nuanced assessment of cervical dystonia.

2. Materials and Methods

2.1. System Architecture

The system architecture integrates 9DOF Movesens sensors placed strategically on the patient's body, particularly on the back of the head above the neck. These sensors communicate via Bluetooth with a custom-designed Android mobile application, which logs the sensor data. The application serves as the interface for data collection, providing a streamlined process for recording and analyzing movement data as the data is stored in the cloud after recording and immediately available to researchers or practitioners for analysis (Figure 2). The architecture emphasizes ease of use and minimal intrusion, with the end goal of allowing for effective data capture in a home environment. This setup enables the continuous monitoring of patients, offering a more comprehensive understanding of the progression and variability of cervical dystonia symptoms over time.

The Movesense Active sensor is a versatile and compact device designed for motion tracking and heart rate monitoring. Equipped with a 9-axis IMU (Inertial Measurement Unit), it provides precise data on movement and orientation. The sensor includes an accelerometer, gyroscope, and magnetometer, enabling it to capture a wide range of motions accurately. Its small size and lightweight design make it ideal for wearable applications, allowing it to be easily integrated into various settings without causing discomfort. This sensor is particularly suitable for detailed motion analysis in medical and sports contexts.

Figure 1. Schematic overview of the system and how data is transferred: first from sensor to mobile app (via Bluetooth), next to the cloud, and finally to the practitioner (both via the internet)

2.2. Mobile Application

We designed an Android mobile application (Figure 1) that communicates with the Movesense sensors and records their data. The app simplifies the connection process and provides clear instructions for each step of the setup, such as placing the sensors in the initial position, attaching them to the participant, and starting the data logging. Once the data collection is done, the application saves the raw sensor data locally on the phone in a CSV format and also transfers it to the cloud for easier access and analysis.

We are also planning to add an additional feature to the app, that will allow users to access statistics related to recorded data. These statistics will provide details such as measurement dates and times, session durations, and identification of specific events during sessions, such as notable angular deviations and their durations.

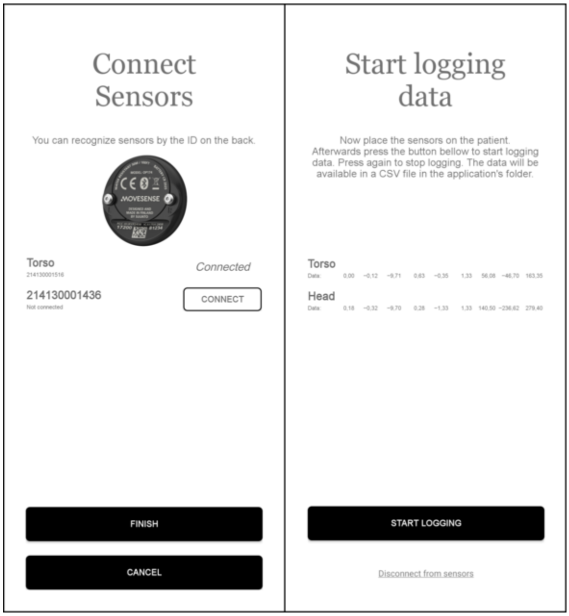

Figure 2. Screenshots showcasing the user interface of the Android mobile application.

The application also enables the user to calibrate the gyroscope and accelerometer of the Movesense sensors to enhance their accuracy. Moreover, it has built-in features to ensure data quality and reliability. For example, it tries to reconnect to a Movesense sensor if the connection is lost and shows the live data from the sensors so that the user can check their normal operation. Additionally, the app indicates the number of expected and received packets from each sensor, so that the user can detect any irregularities.

2.3. Measurement Protocol

The initial methodology used consists of a short protocol designed for evaluating head and neck movements in individuals with cervical dystonia. This protocol involves a series of predefined movements, including rotations, lateral flexions, forward and backward flexions, as well as trembling (tremor) of the head. The movements are designed to systematically capture the range of motion and patterns specific to cervical dystonia. They are presented in Table 1. To give visual feedback to the subject during execution, a special semicircular panel was constructed with angles of different rotations and flexions clearly marked. The subject is then equipped with a laser pointer on the head providing visual feedback for the requested rotations and flexions (see Figure 6). During these exercises, subjects are monitored using the Movesens sensors, providing real-time data on their head and neck movements. Subjects receive instructions for each movement through the mobile app via natural language audio signals. This method ensures clarity and consistency in the execution of the movements.

Table 1. Movement Protocol for assessing CD-specific head movements. Total duration 1 minute. This results in approximately 450kB of data (in a real-world scenario we estimate use of 2 to 3 hours resulting in 50 - 80 MB of data daily).

#	Duration (s)	Label	#	Duration (s)	Label
1	5	neutral	11	5	neutral
2	5	rotation right 90°	12	5	flexion right 35°
3	5	neutral	13	5	neutral
4	5	rotation left 90°	14	5	flexion left 35°
5	5	neutral	15	5	neutral
6	5	flexion fwd 35°	16	5	yes-yes tremor
7	5	neutral	17	5	neutral
8	5	flexion forward 35°	18	5	no-no tremor
9	5	neutral	19	5	neutral
10	5	flexion backward 35°	20	5	complex random tremor

2.4. Reference Measurements

The quality of 9DOF sensors for CD monitoring was assessed with the use of the OptiTrack system [18] that enables high-precision motion capture, serving as a reference standard against which the Movesens sensor data was compared. The OptiTrack system consists of 16 cameras, emitting infrared light and at the same time detecting its reflection from the small reflective markers, that can be positioned on different objects. This allows for a robust validation of the sensor's data accuracy in capturing head and neck movements.

3. Results and Data Analysis

The rotations around the x (roll), y (pitch), and z (yaw) axis of the 9DOF Movesense sensor were obtained from its accelerometer, gyroscope, and magnetometer data, fitted into the Matlab function `ahrsfilter`, which calculates the corresponding rotations using the Kalman filter. To validate the obtained results, the Movesense sensor was fixed on a plate with OptiTrack reflective markers positioned on its corners, as shown in Fig. 3, to allow a synchronous tracking of its motion with the OptiTrack system. For the comparison of the rotation obtained with the Movesense sensor and the Optitrack system, the Movesense rotation angles were expressed in the OptiTrack base coordinate system as

$$\mathbf{M}_i^{\mathrm{Opt}} = \mathbf{M}_i \left(\mathbf{M}_{\mathrm{V},1}^{\mathrm{T}} \mathbf{O}_{\mathrm{V},1} \right), \quad (1)$$

where $\mathbf{M}_i^{\mathrm{Opt}}$ is the i-th rotation matrix of the Movesense sensor expressed in the OptiTrack base coordinate sys-

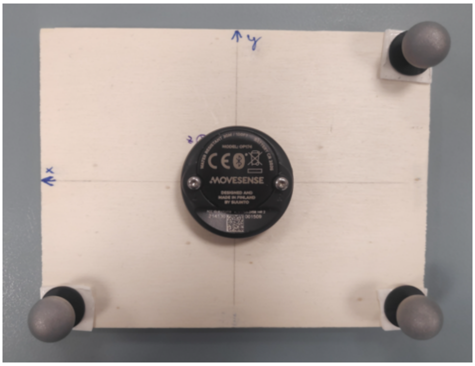

Figure 3. A plate with the Movesense sensor and the OptiTrack reflective markers.

tem, $\mathbf{M}_i$ is the i-th rotation matrix of the Movesense sensor expressed in the Movesense base coordinate system, $\mathbf{M}_{V,1}^{T}$ is the transpose of the first rotation matrix of the Movesense sensor expressed in the Movesense coordinate system, where the relation $\mathbf{M}_{V,1}^{T} = \mathbf{M}_{V,1}^{-1}$ holds, and $\mathbf{O}_{V,1}$ is the first rotation matrix of the OptiTrack rigid body, constructed from the reflective markers positioned on the plate, expressed in the OptiTrack base coordinate system. The index V denotes that these were the validation measurements, while the schematic overview of the coordinate system rotations is shown in Fig. 4.

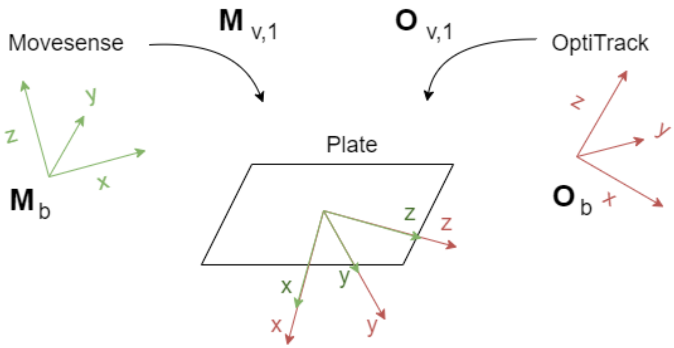

Figure 4. Schematic overview of coordinate systems arrangement during validation. The base Movesense coordinate system ($\mathbf{M}_b$) and the base OptiTrack coordinate system ($\mathbf{O}_b$) were not aligned, while the coordinate systems of the Movesense sensor and the Optitrack rigid body created from the reflective markers positioned on the plate were aligned.

The rotation of the Movesense rotation matrices into the OptiTrack base coordinate system was possible, as the coordinate axes of the Movesense sensor and the Optitrack rigid body were pointing in the same directions. The difference in the rotation angles for some random rotations of the plate obtained from the Movesense sensor and the OptiTrack system are smaller than 3°, as shown in Fig. 5.

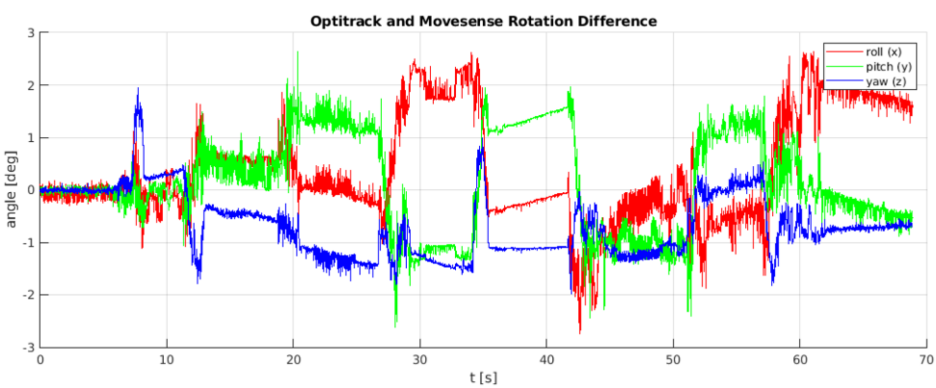

Figure 5. The difference between the reconstructed pitch, roll, and yaw angles obtained from the 9DOF Movesense sensors and the reference OptiTrack system.

After the rotation angles obtained with the Movesense sensor were validated, a measurement of a person, following the base movements from the predefined movement protocol shown in Table 1 was performed. The Movesense sensor was first positioned in such a way that its coordinate axes were aligned with the coordinate axes of the screen: the x axis was pointing horizontally and perpendicularly to the screen, the y axis was pointing upwards, and the z axis was pointing horizontally towards the screen. After the first measurements were performed, the Movesense sensor was placed on the head of the investigated person above its neck, as shown in Fig. 6. The schematic overview of the Movesense coordinate system rotations is shown in Fig 7.

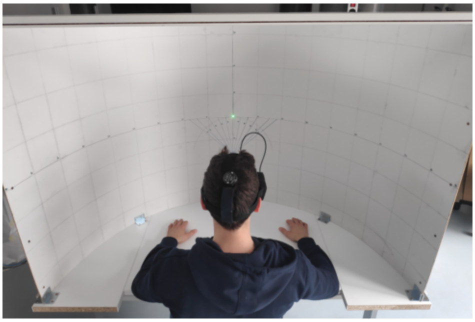

Figure 6. A person sitting in front of the screen wearing the laser pointer and the Movesense sensor on his head.

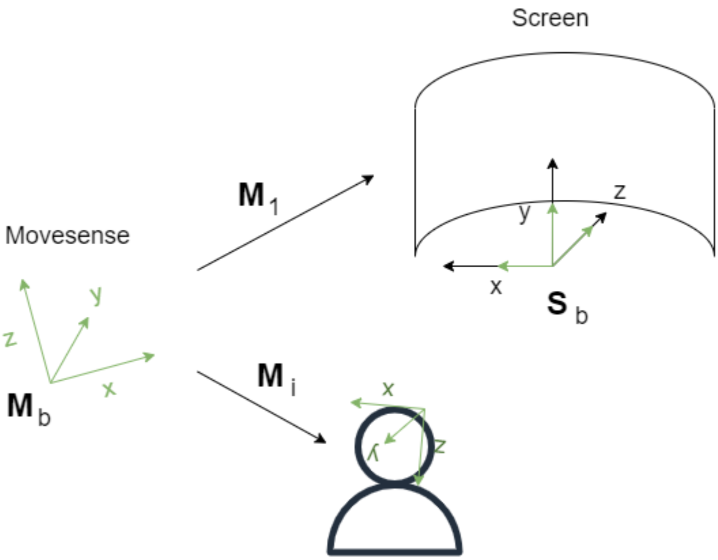

Figure 7. Schematic overview of Movesense coordinate system arrangement during measurements.

The Movesense rotation angles were expressed in the screen coordinate system as

$$\mathbf{M}_i^{\mathrm{sc}} = \mathbf{M}_i \mathbf{M}_1^{\mathrm{T}}, \tag{2}$$

where $\mathbf{M}_i^{\mathrm{sc}}$ is the i-th rotation matrix of the Movesense sensor expressed in the screen coordinate system, $\mathbf{M}_i$ is the i-th rotation matrix of the Movesense sensor expressed in the Movesense base coordinate system, and $\mathbf{M}_1^{\mathrm{T}}$ is the transpose of the 1$^{\mathrm{st}}$ rotation matrix of the Movesense sensor expressed in the Movesense base coordinate system, when the sensor coordinate system was aligned with the screen coordinate system. The rotation angles of the Movesense sensor expressed in the screen coordinate system, obtained by Eq. (2), are shown in Fig. 8

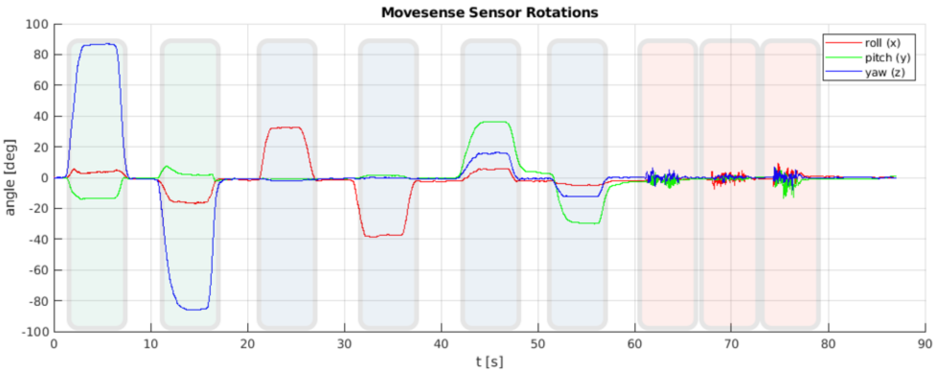

Figure 8. The pitch, roll, and yaw angles obtained from the 9DOF Movesense sensor, placed on the head of the participant, performing head rotations. From left to right the coloured columns highlight rotations 2 and 4 (green), flexions 6, 8, 10, 12 (blue), and tremor 16, 18, 20 (red) from the protocol described in Table 1.

4. Discussion and Future Work

The study's findings highlight that 9DOF sensors are indeed effective in measuring dystonia-specific movements. This is evident in Figure 8, where each type of movement is distinctly identifiable on the chart, suggesting that the sensor can differentiate between the various movement patterns associated with CD.

When comparing the Movesense sensor data with the OptiTrack system, the results show an accuracy within a 3-degree difference. Considering that current clinical assessments are done approximately with the naked eye, this level of accuracy is a substantial improvement and suggests that the Movesense sensor could be a viable tool for practitioners in assessing and monitoring CD symptoms.

4.1. Challenges and Limitations

A notable challenge encountered in the study is the sensor's drift over time, which poses a limitation for continuous monitoring. This drift needs to be effectively compensated for to ensure the reliability of long-term data collection. As the precision analysis in this study was conducted with a single sensor, using multiple sensors on a single participant could potentially improve accuracy and help to compensate for any sensor drift.

The positioning of the sensors is important not only for data accuracy but also for patient comfort and social acceptability. Non-stigmatizing solutions, such as integrating sensors into everyday items like glasses or smart textiles (e.g., hats), could be explored to enhance wearability.

To strengthen the findings, data from a larger cohort of participants is required. Additionally, expanding the protocol to include more movements could yield finer-grained results and a more comprehensive understanding of the disorder.

4.2. Future Work

Future iterations of the system could see the processing of data being transferred from the cloud or a remote machine to the mobile phone. This would allow for immediate feedback to the user, keeping them informed and engaged in the monitoring process. Alternatively, processing could be shifted to the sensor node itself [20], which could conserve energy by transmitting processed data rather than raw data via Bluetooth to the phone.

The sensor's battery life could be enhanced through contextually aware approximate computing [19]. By focusing on disease-specific tremors and discounting data from non-relevant activities (like riding a bus), the system could adjust the accuracy and sampling frequency, conserving energy when high precision is not necessary. The exploration of machine learning techniques to classify movements directly based on raw sensor data holds promise for further automating and refining the assessment of CD.

In advancing the presented tool for continuous monitoring tool of cervical dystonia, we will release the Android app's APK (named CerviTrack) for practitioners to test. The app's source code and processing scripts will also be published, supporting further research and development within the community.

5. Conclusion

In conclusion, our study offers promising insights into the use of 9DOF sensors for the precise monitoring of CD. The main results indicate that these sensors can effectively differentiate dystonia-specific movements and are a viable way towards continuous monitoring of CD symptoms.

Acknowledgements

This work was supported by the Slovenian Research Agency (grant P2-0098, grant P2-0076, and project J2-3047). The sensors used where provided as part of the Movesense academic program.

References

[1] Fahn S., Marsden C. D., Calne D.B. (1987) Classification and investigation of dystonia. In: Marsden CD, Fahn S, eds: Movement Disorders London, Butterworth Scientific: 332-358

[2] Dressler, D., Altenmüller, E., Giess, R., Krauss, J. K., and Adib Saberi, F. (2022). The epidemiology of dystonia: the Hannover epidemiology study. Journal of Neurology, 269(12), 6483-6493.

[3] Girach, A., Julian, T. H., Varrassi, G., Paladini, A., Vadalouka, A., and Zis, P. (2019). Quality of life in painful peripheral neuropathies: a systematic review. Pain Research and Management, 2019.

[4] Münchau, A., Filipovic, S. R., Oester-Barkey, A., Quinn, N. P., Rothwell, J. C., and Bhatia, K. P. (2001). Spontaneously changing muscular activation pattern in patients with cervical dystonia. Movement disorders: official journal of the Movement Disorder Society, 16(6), 1091-1097.

[5] Comella, C. L., Perlmutter, J. S., Jinnah, H. A., Waliczek, T. A., Rosen, A. R., Galpern, W. R., ... and Stebbins, G. T. (2016). Clinimetric testing of the comprehensive cervical dystonia rating scale. Movement Disorders, 31(4), 563-569.

[6] Zetterberg, L., Halvorsen, K., Färnstrand, C., Lundström, E., Lindmark, B., and Aquilonius, S. M. (2005). Objective assessment of cervical dystonia: a pilot study. Acta neurologica scandinavica, 112(4), 248-253.

[7] Galardi, G., Micera, S., Carpaneto, J., Scolari, S., Gambini, M., and Dario, P. (2003). Automated assessment of cervical dystonia. Movement Disorders: Official Journal of the Movement Disorder Society, 18(11), 1358-1367.

[8] Carpaneto, J., Micera, S., Galardi, G., Micheli, A., Carboncini, M. C., Rossi, B., and Dario, P. (2004). A protocol for the assessment of 3D movements of the head in persons with cervical dystonia. Clinical biomechanics, 19(7), 659-663.

[9] Caronni, A., Arcuri, P., Carpinella, I., Marzegan, A., Lencioni, T., Ramella, M., ... and Castagna, A. (2022). Smoothness of movement in idiopathic cervical dystonia. Scientific Reports, 12(1), 5090.

[10] Brin, M. F., Fahn, S., Moskowitz, C., Friedman, A., Shale, H. M., Greene, P. E., ... and McMahon, D. (1987). Localized injections of botulinum toxin for the treatment of focal dystonia and hemifacial spasm. Movement disorders: official journal of the Movement Disorder Society, 2(4), 237-254.

[11] Comella CL, Jankovic J, Hauser RA, Patel AT, Banach MD, Ehler E, Vitarella D, Rubio RG, Gross TM; (2024)ASPEN-1 Study Group. Efficacy and Safety of DaxibotulinumtoxinA for Injection in Cervical Dystonia: ASPEN-1 Phase 3 Randomized Controlled Trial. Neurology. Feb 27;102(4).

[12] Reichel, G. (2011). Cervical dystonia: a new phenomenological classification for botulinum toxin therapy. Basal Ganglia, 1(1), 5-12.

[13] Jost, W. H., Tatu, L., Pandey, S., Sławek, J., Drużdż, A., Biering-Sørensen, B., ... and Kreisler, A. (2020). Frequency of different subtypes of cervical dystonia: A prospective multicenter study according to Col–Cap concept. Journal of Neural Transmission, 127, 45-50.

[14] Trott, P. H., Pearcy, M. J., Ruston, S. A., Fulton, I., and Brien, C. J. C. B. (1996). Three-dimensional analysis of active cervical motion: the effect of age and gender. Clinical Biomechanics, 11(4), 201-206.

[15] Ye, C., Xiao, Y., Li, R., Gu, H., Wang, X., Lu, T., and Jin, L. (2022). Pilot Feasibility Study of a Multi-View Vision Based Scoring Method for Cervical Dystonia. Sensors, 22(12), 4642.

[16] Samotus, O., Lee, J., and Jog, M. (2020). Standardized algorithm for muscle selection and dosing of botulinum toxin for Parkinson tremor using kinematic analysis. Therapeutic advances in neurological disorders, 13, 1756286420954083.

[17] Berbakov, L., Jovanović, Č., Svetel, M., Vasiljević, J., Dimić, G., and Radulović, N. (2019). Quantitative assessment of head tremor in patients with essential tremor and cervical dystonia by using inertial sensors. Sensors, 19(19), 4246.

[18] https://optitrack.com/

[19] Pejović, V. "Towards approximate mobile computing." GetMobile: Mobile Computing and Communications 22.4 (2019): 9-12.

[20] Scrugli, M. A., et al. "A microcontroller-based platform for cognitive tracking of sensorimotor training." IEEE Access (2023).