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Original article

Validity of an inertial measurement unit for the assessment of range and quality of movement during head and thoracic spine movements

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ABSTRACT

Background: Patients with spinal pain often exhibit movement limitations and altered motor control, which can be challenging to measure accurately in clinical practice. Inertial measurement sensors present a promising new opportunity to develop valid, low-cost, and easy-to-use methods for assessing and monitoring spinal motion in a clinical setting.

Aim: This study aimed to investigate the agreement of an inertial sensor and a 3D camera system for assessing the range of motion (ROM) and quality of movement (QOM) in head and trunk single-plane movements.

Methods: Thirty-three healthy, pain-free volunteers were included. Each participant performed movements of the head (cervical flexion, extension, and lateral flexion) and trunk (trunk flexion, extension, rotation, and lateral flexion), which were simultaneously recorded by a 3D camera system and an inertial measurement unit (*MOTI, Aalborg, Denmark*). Agreement and consistency were analyzed for ROM and QOM by determining intraclass correlation coefficients (ICC), mean bias, and with Bland-Altman plots.

Results: The agreement between systems was excellent for all movements (ICC between 0.91 and 1.00) for ROM and good to excellent for the QOM (ICC between 0.84 and 0.95). The mean bias for all movements (0.1–0.8°) was below the minimum acceptable difference between devices. The Bland-Altman plot indicated that MOTI systematically measured a slightly greater ROM and QOM than the 3D camera system for all neck and trunk movements.

Conclusion: This study showed that MOTI is a feasible and potentially applicable option to assess ROM and QOM for head and trunk movements in experimental and clinical settings.

Declaration of interest

Steffan Wittrup McPhee Christensen, Rogerio Pessoto Hirata & Thorvaldur Skuli Palsson are co-founders of MOTI. They did not participate in data collection or statistical analysis.

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1. Introduction

Spine-related pain is the leading cause of rehabilitation needs worldwide (Cieza et al., 2021) and a common reason for people seeking care. When compared to healthy controls, people with neck pain frequently present with a reduced cervical range of motion (ROM) and altered sensorimotor control strategies such as poorer repositioning sense or reduced quality of movement (QOM), which can be quantified as higher movement jerkiness (Franov et al., 2022; Hesby et al., 2019; Moghaddas et al., 2019).

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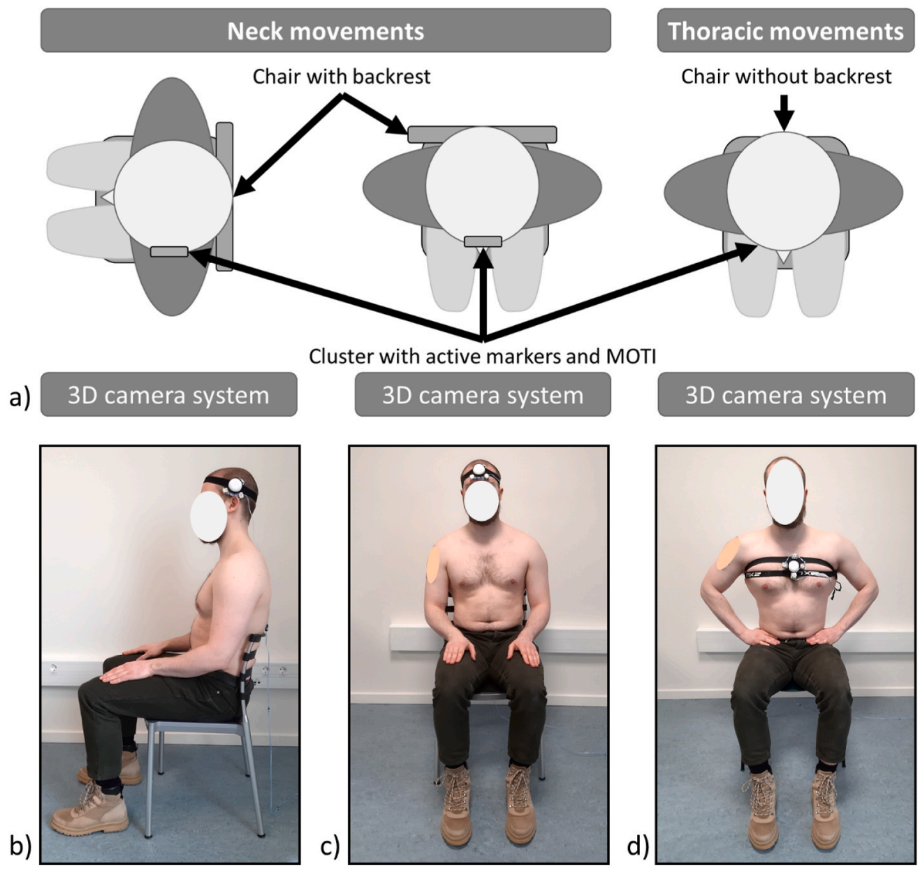

Fig. 1. Picture of setup (a) and custom cluster for cervical (b & c) and trunk (d) movements.

Interestingly, despite clinical guidelines and reviews advocating the inclusion of the thoracic spine when assessing and managing neck pain (Blanpied et al., 2017; Joshi et al., 2019), thoracic movement dysfunction is still poorly understood (Heneghan and Rushton, 2016; Heneghan et al., 2018). Only a few studies have objectively investigated movement features of the thoracic spine in neck pain populations (Heneghan et al., 2018; Joshi et al., 2019). However, the transferability from these studies to clinical practice assessment has been limited since the studies (Falla et al., 2017; Treleaven et al., 2019; Tsang et al., 2014) primarily used expensive high-tech equipment which is often limited to research laboratories and requires expert knowledge to use.

Technological advancements during the past decades have made it possible to use everyday devices such as smartphones for assessing head ROM (Elgueta-Cancino et al., 2022), while assessing the quality of movement (QOM) has so far been far more challenging, especially in a clinical setting. In addition, when considering the trunk, there are far fewer options (Furness et al., 2018; Johnson et al., 2012; Moghaddas et al., 2022; Morita et al., 2014; Takatalo et al., 2020). Optoelectronic motion capture systems, such as 3D-camera systems, are commonly used for assessing spinal movements (Papi et al., 2017). However, employing these methods in clinical practice is not feasible due to the costs, time, and expertise required for implementation. With this in mind, inertial measures sensors could be considered an alternative for clinical use to record relevant movement variables (Poitras et al., 2019). A recent study (Christensen et al., 2023) compared an inertial measuring unit to a 3D-camera for recordings of head rotations and showed good to excellent agreement for both ROM & QOM. However, the previous study was limited by only investigating movements in the transverse plane (rotation), and it was suggested that future studies should investigate movement in the sagittal and coronal planes to cover all movements included in a clinical assessment of the cervical spine (Christensen et al., 2023). Being able to use an inertial measuring unit in a clinical setting may allow for an objective recording of factors commonly used in a clinical evaluation of cervical and thoracic motion, such as ROM and QOM, and thereby aid clinical decision-making, as well as evaluate the effect of rehabilitation interventions (Christensen et al., 2023).

This study aimed to determine the concurrent validity and reliability of an inertial measurement unit, MOTI, for recording head and trunk ROM and QOM by comparing it to a 3D-camera system.

2. Methods

2.1. Design

This cross-sectional observational study followed the Guidelines for Reporting Reliability and Agreement Studies (GRRAS) (Kottner et al., 2011) while adhering to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) checklist for observational studies (von Elm et al., 2007).

2.2. Participants

Thirty-three healthy male participants were recruited from a university setting by convenience sampling. The inclusion criteria were: ≥18 years old, having no pain from any region of the body, having a normal pain-free ROM of neck and trunk movements, and being able to speak and read Danish or English. Exclusion criteria were a score >4 points (8%) on the Neck Disability Index (NDI) (Vernon, 2008), any history of pain related to the neck or thoracic spine during the past six months, any musculoskeletal, rheumatoid, or neurological condition (e.g., fibromyalgia, rheumatoid arthritis, ankylosing spondylitis, multiple sclerosis) that could influence a normal pain-free ROM along with any previous history of cervical or thoracic surgery. Before commencing the study, all participants provided informed consent, after which a

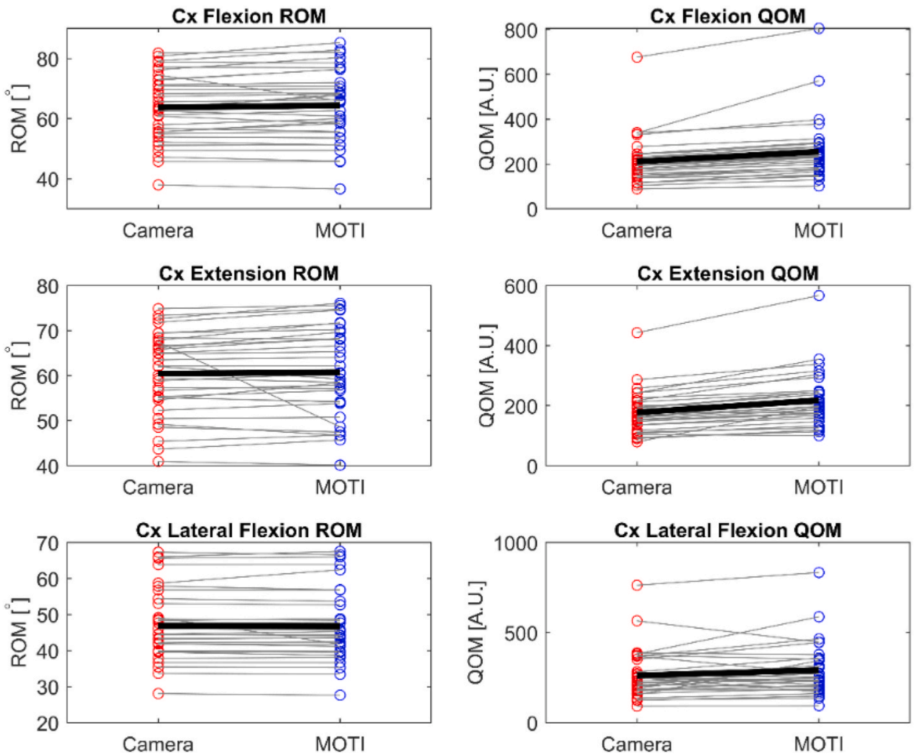

Fig. 2. Individual measures plot with the paired dots connected for head (Cx) movements: ROM and QOM. The thick black line indicates the mean value.

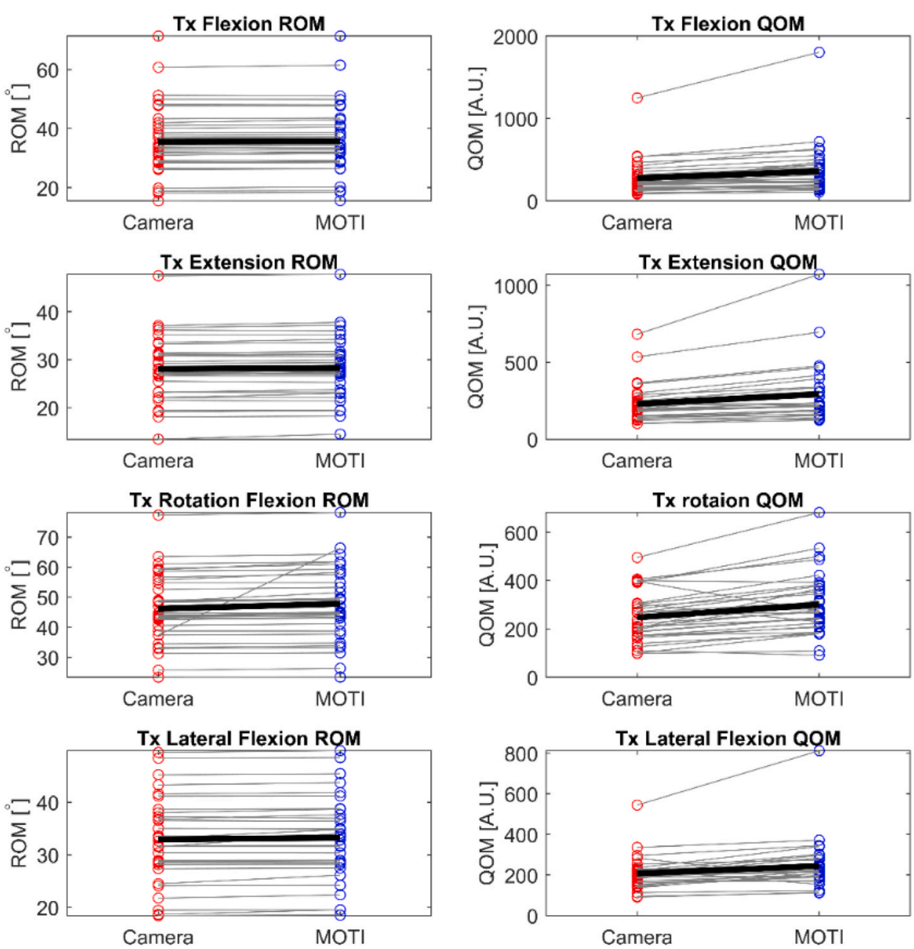

Fig. 3. Individual measures plot with the paired dots connected for trunk (Tx) movements: ROM and QOM. The thick black line indicates the mean value.

Table 1
Range of motion (ROM) for all participants (N = 33) during head (Cx) and trunk (Tx) movements: Mean bias (ROM: ° (SD)), limits of agreement, and inter-class correlation (ICC; 2.1) between camera and MOTI.

	Mean bias (Camera – MOTI)	Limits of agreement	ICC
Cx Flexion ROM	−0.7 (2.6)	(-5.8) – (4.34)	0.975
Cx Extension ROM	−0.3 (3.8)	(-7.7) – (7.1)	0.919
Cx Lateral flexion ROM	0.2 (1.4)	(-1.6) – (1.5)	0. 997
Tx Flexion ROM	−0.2 (0.3)	(-0.7) – (0.4)	0.999
Tx Extension ROM	−0.2 (0.4)	(-0.9) – (0.4)	0.999
Tx Rotation ROM	−0.8 (0.8)	(-2.2) – (0.7)	0.913
Tx Lateral ROM	−0.3 (0.6)	(-1.5) – (0.8)	0.997

Table 2
Quality of movement (QOM) for all participants (N = 33) during head (Cx) and trunk (Tx) movements: Mean bias: (QOM: A.U. (SD)), limits of agreement, and inter-class correlation (ICC; 2.1) between camera and MOTI.

	Mean bias (Camera – MOTI)	Limits of agreement	ICC
Cx Flexion QOM	−44.2 (39.7)	(-33.6) – (122.0)	0.945
Cx Extension QOM	−40.5 (30.6)	(-100.5) – (19.5)	0.926
Cx Lateral flexion QOM	−29.3 (69.5)	(-165.5) – (106.8)	0.874
Tx Flexion QOM	−83.3 (103.8)	(-120.0) – (286.7)	0.922
Tx Extension QOM	−63.3 (71.4)	(-203) – (76.7)	0.893
Tx Rotation QOM	- 53 (61.5)	(-174.0) – (67.0)	0.853
Tx Lateral QOM	−37.4 (58.1)	(-151.3) – (76.5)	0.835

physiotherapist conducted a short physical examination to ensure normal pain-free cervical and thoracic ROM. The study was conducted in accordance with the rules and regulations of the regional ethical committee, which state that studies aimed at calibration and validation of measurement devices do not require ethical approval (The National Committee on Health Research Ethics, 2019).

A sample size calculation was conducted using MedCalc Software Ltd (*version 20.110, Ostend, Belgium)* to determine the minimum number of observations required for Bland–Altman agreement analysis (Lu et al., 2016). An expected mean bias for ROM of 0.66° and an SD of 0.72° was made based on a previous study (Christensen et al., 2023). Additionally, a maximum tolerated difference was established at 3° (Jørgensen et al., 2017). Therefore, with an alpha value of 0.01 and a power of 90%, 33 participants were needed.

2.3. Experimental setup

All assessments were performed with the participants sitting in a comfortable position with feet placed flat on the floor with hips and knees flexed at approximately 90°. Participants sat at an oblique angle to the 3D camera system to ensure that the markers were visible throughout the movement (Fig. 1a). For cervical movements, participants had their forearms resting on their thighs while seated in a chair with a backrest (Fig. 1b and c). For trunk movements, participants placed their hands above the iliac crests while seated on a chair without a backrest (Fig. 1d). Prior to each new movement direction for the head or trunk, participants were instructed to assume their self-chosen upright seated position. To limit movement artifacts between the 3D camera markers and MOTI (*MOTI, Aalborg, Denmark*), they were all fixated on the same plastic cluster (Fig. 1b and c & d). Attaching an inertial measurement along with markers for 3D motion capture to the same rigid plastic surface for assessing validity and reliability has previously been used for head, trunk, and lower limb movements (Brice et al., 2020; Brouwer et al., 2021; Christensen et al., 2023; Rattanakoch et al., 2023; Teufl et al., 2019). For cervical movements, two 3D markers and MOTI were placed on a piece of plastic and mounted on a headband (total weight 71g) to assess flexion and extension (fig, 1b) and lateral flexion (Fig. 1c). For trunk movements, a custom-made cluster was 3D printed and mounted with four markers (two horizontal and two vertical) together with the MOTI unit and placed on the sternum (Fig. 1d). The two vertical markers on the chest cluster were used to create the movement vector for trunk flexion and extension, while the two horizontal markers were used for lateral flexion and rotation movements.

2.4. Assessment methods

A 3D camera system (*Optotrak, Waterloo, Ontario, Canada*) using active markers was used to record the kinematics. The spatial coordinates of the markers were determined by the Optotrak software (*NDI International, Waterloo, Ontario, Canada*) with an accuracy of 0.1 mm and a resolution of 0.01 mm (NDI, 2017), which has been commended for its ability to assess movement in great detail (Bailon et al., 2019; Cunningham and Brooks, 2022).

MOTI (*MOTI, Aalborg, Denmark*) is a commercially available inertial measurement unit. MOTI utilizes sensor fusion techniques to combine the raw measurements from the magnetometer, accelerometer, and gyroscope to calculate a quaternion orientation of the device. MOTI then uses a proprietary algorithm that uses these series of quaternions to calculate the differential angle. The entire waveform of the differential angle was extracted and trimmed to the start and end of the movement. MOTI was connected to a smartphone (*Samsung Galaxy A12, Samsung Electronics, Suwon, Korea*) via Bluetooth. Data were sampled at 83.5 Hz and recorded using a mobile application (*MOTI-Research, version RC1, Aalborg, Denmark*).

2.5. Protocol

Before commencing data collection, the assessor (PBL) carefully explained all experimental procedures to the participants, including that all movements had to be performed throughout full range without compensatory movements from other body parts.

The assessor demonstrated all the movements, and the participants performed a familiarization trial before data collection started. The participants performed spinal movements in the following order: (1) cervical flexion, (2) cervical extension, (3) right cervical lateral flexion, (4) trunk flexion, (5) trunk extension, (6) right trunk rotation, and (7) right trunk lateral flexion. Participants performed three repetitions of each task before proceeding to the next task. Only right-sided movements were assessed, as the aim of this study was not to investigate side differences. Additionally, cervical rotation was omitted in the current study as this has already been covered in a previous study (Christensen et al., 2023).

2.6. Signal processing

ROM was defined as the angle between the start and end position of the head or trunk movements. The angle was directly extracted from the MOTI device but for the 3D camera system, two 3D vectors defined by the markers were used to calculate the arctangent. The first vector corresponded to the initial natural resting positions, determined as the average of the initial 15 frames before movement onset. The second vector was calculated during the head or trunk movements and represented the neck or sternum positions over time. All processed signals were analyzed similarly for both systems via a custom-made script in MATLAB (*v.R2022a, The MathWorks, Inc., Natick, Massachusetts, USA*). All data were automatically trimmed between the start and end of the movement. The start of the movement was defined as the time point when the orientation angle was 2% larger than the average of the first 20 data points. The end of the movement was when the orientation angle was 2% smaller than the average of the first 20 data points. Data for the angular position were filtered with a low-pass Butterworth filter (zero lag, 1.5 Hz, fourth order) (Christensen et al., 2023; Palsson et al., 2019).

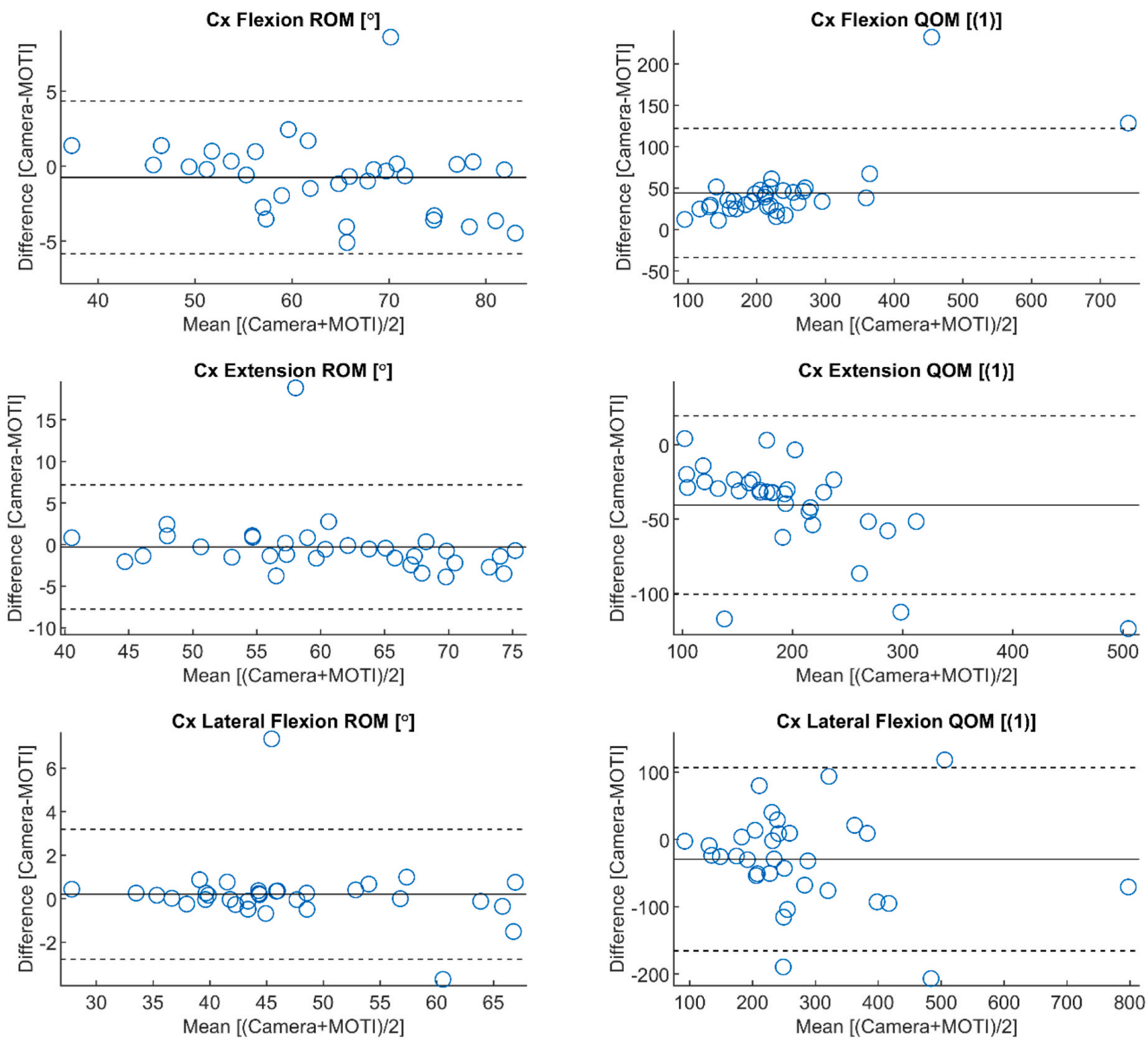

Fig. 4. Bland-Altman plots for head/cervical (Cx) movements: ROM and QOM. The continuous line represents the mean of differences, and the dotted lines represent the limits of agreement. ROM was measured in degrees [°] and QOM is unitless [(1)].

Sequential derivatives of the angle were performed to calculate angular velocity, acceleration, and jerk over time.

QOM was defined as the time integral of the squared jerk between the start and end of the movement (Sjölander et al., 2008). QOM was calculated as the time integral of the squared jerk (equation (1)) (Hogan and Sternad, 2009; Yan et al., 2000). The normalized jerk was made unitless by multiplying the integrated squared angular jerk (J) with movement time (T) lifted to the power of five divided by the squared range of the movement (θ) (Christensen et al., 2023; Hogan and Sternad, 2009; Yan et al., 2000).

$$Normalized\ Jerk = \sqrt{\frac{1}{2} \bullet \int J^2(t) \bullet \frac{T^5}{\theta^2} dt} \qquad \text{(equation 1)}$$

2.7. Statistical analysis

Data distribution was assessed using the Shapiro-Wilk test. The Agreement of ROM and QOM recordings between the 3D camera system and MOTI were evaluated for single measurement absolute agreement, based on a two-way random model, by computing intraclass correlation coefficients ($ICC_{2,1}$). An ICC above 0.90 was interpreted as "excellent", between 0.75 and 0.90 "good", between 0.50 and 0.75 "moderate", and less than 0.50 "poor" (Koo and Li, 2016). Bland-Altman plots for ROM and QOM were used for visual inspection of agreement between the measurements of the two devices (Bland and Altman, 1986).

Statistical analysis was performed using SPSS v.28 (*IBM, Chicago, IL, USA*). The Bland & Altman plots were performed in Matlab (*R2022a, The MathWorks, Inc., Natick, Massachusetts, USA*). Significance was accepted at $P < 0.05$.

3. Results

The participants had a mean age of 30.7 (SD: 5.9; range 21–45) years, a mean height of 180.8 (SD: 5.1) cm, and a mean weight of 83.0 (SD: 12.3) kg. For cervical and head movements (Fig. 2), the camera recorded means of: 63.7° (SD:11.2) flexion, 60.4° (SD: 9.0) extension, and 47.0° (SD: 9.8) lateral flexion of the neck and head. For trunk movements (Fig. 3), the camera recorded means of: 35.6° (SD: 11.9) flexion, 28.1° (SD: 6.6) extension, 46.2° (SD: 11.6) rotation, and 32.9° (SD: 7.9) lateral flexion.

The agreement was excellent in all ROM in movements, with an $ICC_{2,1}$ ranging between 0.91 and 1.00 (Table 1). For QOM, agreement ranged from good to excellent, with an $ICC_{2,1}$ ranging between 0.84 and 0.95 (Table 2).

From the results, MOTI overestimated ROM <0.8° (Table 1, Fig. 2, and Fig. 3) and QOM (Table 2, Fig. 2, and Fig. 3) compared to what was seen for the 3D camera, which is also evident from the Bland-Altman

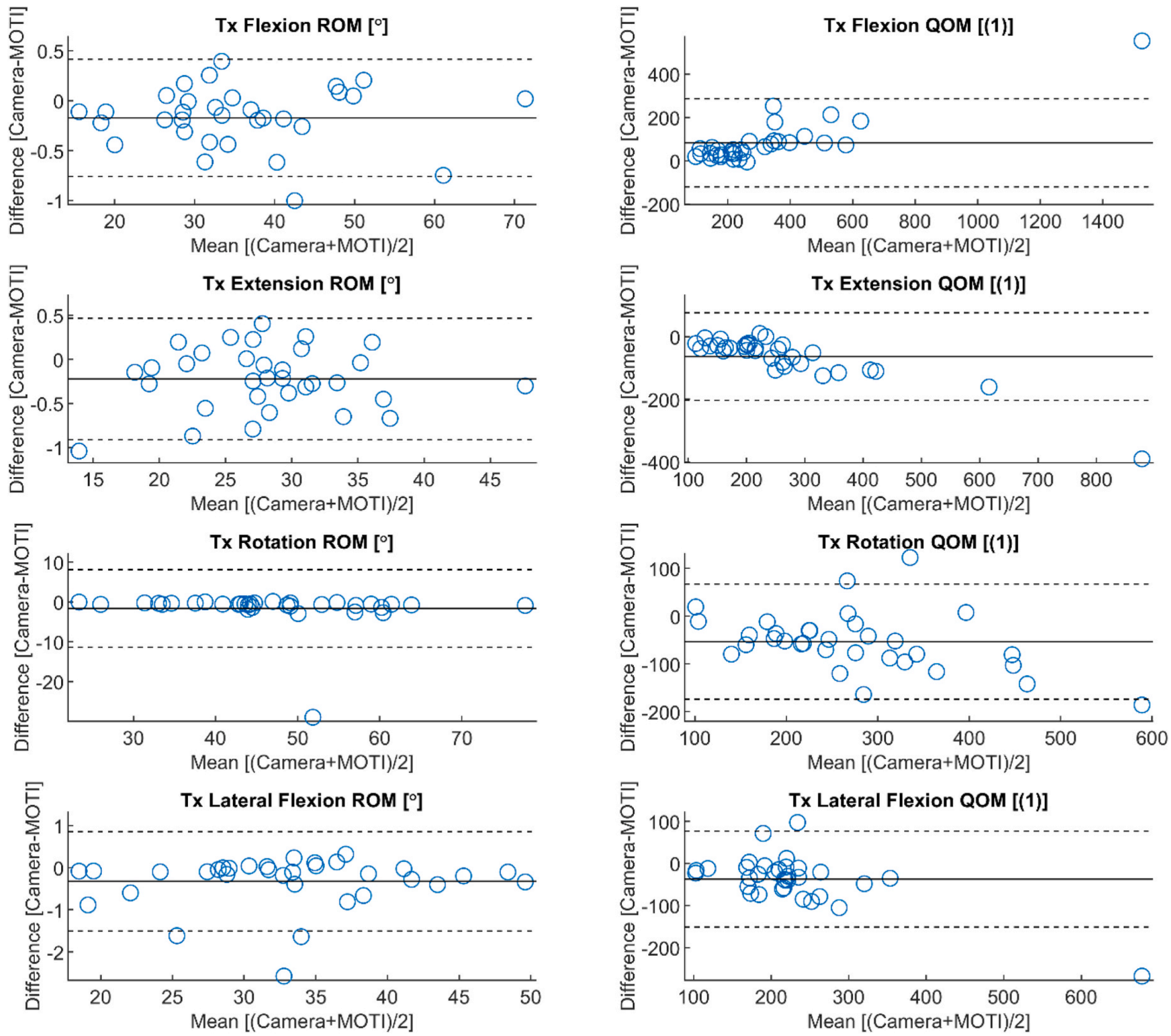

Fig. 5. Bland-Altman plots for trunk/thoracic (Tx) movements: ROM and QOM. The continuous line represents the mean of differences, and the dotted lines represent the limits of agreement. ROM was measured in degrees [°] and QOM is unitless [(1)].

plots for both cervical (Fig. 4) and trunk (Fig. 5) movements.

4. Discussion

This cross-sectional study investigated the concurrent validity and reliability of using MOTI and a 3D camera system for measuring ROM and QOM of both the neck and trunk. For ROM, excellent agreement was found for all movements irrespectively of the body region, while good to excellent agreement was seen for QOM, indicating that the two methods produced comparable results.

4.1. Assessing clinically meaningful neck and trunk movements

The current results indicate that the inertial measurement unit, MOTI, could be used to assess ROM and QOM accurately for neck and trunk movements, which is in line with previous findings for movements in the transverse plane (Christensen et al., 2023). Considering both the previous and the current results, MOTI is therefore a feasible option to consider in future research studies as well as in clinical practice for recording head and trunk motion. The current ROM for head movements were similar to the reference values for a healthy adult population in their thirties for flexion and extension (55°–70°) and lateral flexion (40°–43°) movements (Chen et al., 1999; Thoomes-de Graaf et al., 2020). Furthermore, while there is a lack of normative values for ROM in trunk movements, previous studies assessing with goniometry trunk rotation in a sitting position showed similar values in a healthy population (41°–55°) (Johnson et al., 2012) and higher ROM of flexion and extension than a population with thoracic spine pain (Takatalo et al., 2020).

For clinicians managing cervical disorders, assessing ROM is highly relevant for identifying movement limitations or asymmetries that may support the clinical decision-making process (Hesby et al., 2019; Stenneberg et al., 2017). For example, in chronic neck pain patients, reduced ROM at the start of treatment has been identified as a prognosis factor of higher pain and disability 6-months after treatment (Weigl et al., 2021). Moreover, the ability to assess QOM in clinical settings opens up new opportunities to detect more complex and advanced movement characteristics that may further guide management (Franov et al., 2022), which would not be possible with analogue clinical tools. This study found excellent agreement values between MOTI and the 3D camera system for ROM and QOM, indicating that the two devices detect the change in motion and position in a similar manner. Additionally, the systematic nature of the bias when interpreting ROM mean bias, which was below the threshold of the minimum acceptable difference between devices of 3° (Jørgensen et al., 2017), supports using MOTI for assessing neck ROM and QOM in a clinical setting.

Regarding the assessment of thoracic spine kinematics, previous studies have used methods such as goniometer, inclinometer, smartphones, and tape (Bucke et al., 2017; Johnson et al., 2012; Takatalo et al., 2020); spinal mouse (Özer Kaya and Çelenay S, 2017); 3D kinematic systems (Falla et al., 2017; Moghaddas et al., 2019); dual inertial sensor laboratory systems (Treleaven et al., 2019); electromagnetic tracking devices (Tsang et al., 2014); and computed tomography (Morita et al., 2014). Furthermore, in validation studies, a manual handheld goniometer has been used as the comparator when evaluating ROM (Furness et al., 2018), where the experience and expertise of the assessor are highly important (Keogh et al., 2019). Another study compared the validity of a digital inclinometer to a smartphone with a clinometer app for assessing ROM and found that these technologies could be used interchangeably (Bucke et al., 2017). In any case, the previous studies are limited to the assessment of ROM with no studies assessing QOM of thoracic spine movements. The present study confirmed the concurrent validity of the inertial measurement unit for measuring ROM and QOM of trunk movements, bringing to the research and clinical fields a potential new measure of assessment.

4.2. Methodologic considerations

A major limitation of the current study is the lack of fixation of other body regions than the one moving. This means that during head movements, the trunk was only supported by the backrest of the chair, and it cannot be ruled out that small trunk movements occurred that were not detected by visual inspection. Similarly, pelvic anteversion/retroversion was not controlled during trunk movements, which in turn may have impacted the results. However, as the participants were reminded to resume their self-chosen upright seated position prior to each new movement direction and each movement repetition was visually inspected to identify any potential deviation from the protocol, the seated posture is not believed to have changed between repetitions. In addition, it is important to note that the markers were placed on the skin of the subject, which may move slightly differently when compared to the underlying bony structure (Bucke et al., 2017; Heneghan and Balanos, 2010). However, it is important to remember that the limitations outlined above are the same for the majority of tests for assessing ROM commonly used in clinical practice. Taken together, when considering the aim of the current study was to determine the validity and reliability of MOTI compared to a 3D camera system, we do not believe that the outlined limitation has impacted the results. Nonetheless, future studies should explore validity against imaging modalities allowing for accurate detection of bony movements.

For accessibility, only men were included in the current study due to the size and placement of the plastic cluster to which MOTI was attached over the sternum for the trunk movements (Fig. 1d). However, we do not consider this to have affected the current findings, considering that no differences in ROM between men and women (Thoomes-de Graaf et al., 2020).

In this study, only healthy participants were included to reduce the potential influence on measurements of factors such as pain or pain-related fear of movement (Asiri et al., 2021). However, future studies need to replicate this setup in a clinical population, evaluating the suitability and feasibility of using the device for assessing the measurements in a clinical setting.

Head and trunk movements were not evaluated randomly but in the same order for all participants. However, a familiarization trial was conducted for each movement before starting the data collection to avoid potential distortions in the way of moving and reduce learning in test performance (Tsigilis and Theodosiou, 2008). Furthermore, as all participants had pain-free ROM, the order of movements is unlikely to have influenced the results. In addition, lateral flexion and rotation movements were only evaluated on the right side as previous reviews have shown no differences in the ROM of the healthy population when comparing sides (Thoomes-de Graaf et al., 2020). Nevertheless, it would have been an added value to evaluate both rotation and lateral flexion movements bilaterally to test if this lack of difference in ROM between sides in a healthy population would also have been the case for QOM recordings.

4.3. Conclusion

Technological devices have made it possible to systematically collect, store, and process complex data (Azodo et al., 2020). By using assessment methods over time as described in this study, reference values for clinical and research purposes can be established to objectively track progression or stagnation. However, before implementing these assessment methods, it is imperative to compare them to other currently used modalities.

The positive findings from this study indicate that MOTI can be a valuable tool to support clinical decision-making. However, future studies need to determine the feasibility of using MOTI in a clinical setting.

References

Asiri, F., Reddy, R.S., Tedla, J.S., Ma, A.L., Alshahrani, M.S., Govindappa, S.C., Sangadala, D.R., 2021. Kinesiophobia and its correlations with pain, proprioception, and functional performance among individuals with chronic neck pain. PLoS One 16, e0254262. https://doi.org/10.1371/journal.pone.0254262.

Azodo, I., Williams, R., Sheikh, A., Cresswell, K., 2020. Opportunities and challenges surrounding the use of data from wearable sensor devices in Health care: qualitative interview study. J. Med. Internet Res. 22, e19542 https://doi.org/10.2196/19542.

Bailon, C., Damas, M., Pomares, H., Banos, O., 2019. SPIRA: an automatic system to support lower limb injury assessment. J. Ambient Intell. Hum. Comput. 10, 2111–2123. https://doi.org/10.1007/s12652-018-0722-6.

Bland, J.M., Altman, D.G., 1986. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1, 307–310.

Blanpied, P.R., Gross, A.R., Elliott, J.M., Devaney, L.L., Clewley, D., Walton, D.M., Sparks, C., Robertson, E.K., 2017. Neck pain: revision 2017. J. Orthop. Sports Phys. Ther. 47, A1–A83. https://doi.org/10.2519/jospt.2017.0302.

Brice, S.M., Phillips, E.J., Millett, E.L., Hunter, A., Philippa, B., 2020. Comparing inertial measurement units and marker-based biomechanical models during dynamic rotation of the torso. Eur. J. Sport Sci. 20, 767–775. https://doi.org/10.1080/17461391.2019.1666167.

Brouwer, N.P., Yeung, T., Bobbert, M.F., Besier, T.F., 2021. 3D trunk orientation measured using inertial measurement units during anatomical and dynamic sports motions. Scand. J. Med. Sci. Sports 31, 358–370. https://doi.org/10.1111/sms.13851.

Bucke, J., Spencer, S., Fawcett, L., Sonvico, L., Rushton, A., Heneghan, N.R., 2017. Validity of the digital inclinometer and iPhone when measuring thoracic spine rotation. J. Athl. Train. 52, 820–825. https://doi.org/10.4085/1062-6050-52.6.05.

Chen, J., Solinger, A.B., Poncet, J.F., Lantz, C.A., 1999. Meta-analysis of normative cervical motion. Spine 24, 1571–1578. https://doi.org/10.1097/00007632-199908010-00011.

Christensen, S.W.M., Palsson, T.S., Djurtoft, C., Simonsen, M.B., 2023. Agreement between a 3D camera system and an inertial measurement unit for assessing the range of motion, head repositioning accuracy and quality of movement during neck and head movements. European Journal of Physiotherapy 1–8. https://doi.org/10.1080/21679169.2023.2198562.

Cieza, A., Causey, K., Kamenov, K., Hanson, S.W., Chatterji, S., Vos, T., 2021. Global estimates of the need for rehabilitation based on the global burden of disease study 2019: a systematic analysis for the global burden of disease study 2019. Lancet 396, 2006–2017. https://doi.org/10.1016/s0140-6736(20)32340-0.

Cunningham, B.W., Brooks, D.M., 2022. Comparative analysis of optoelectronic accuracy in the laboratory setting versus clinical operative environment: a systematic review. Global Spine J. 12, 59s–74s. https://doi.org/10.1177/21925682211035083.

Elgueta-Cancino, E., Rice, K., Abichandani, D., Falla, D., 2022. Measurement properties of smartphone applications for the measurement of neck range of motion: a systematic review and meta analyses. BMC Muscoskel. Disord. 23, 138. https://doi.org/10.1186/s12891-022-05066-6.

Falla, D., Gizzi, L., Parsa, H., Dieterich, A., Petzke, F., 2017. People with chronic neck pain walk with a stiffer spine. J. Orthop. Sports Phys. Ther. 47, 268–277. https://doi.org/10.2519/jospt.2017.6768.

Franov, E., Straub, M., Bauer, C.M., Ernst, M.J., 2022. Head kinematics in patients with neck pain compared to asymptomatic controls: a systematic review. BMC Muscoskel. Disord. 23, 156. https://doi.org/10.1186/s12891-022-05097-z.

Furness, J., Schram, B., Cox, A.J., Anderson, S.L., Keogh, J., 2018. Reliability and concurrent validity of the iPhone(®) Compass application to measure thoracic rotation range of motion (ROM) in healthy participants. PeerJ 6, e4431. https://doi.org/10.7717/peerj.4431.

Heneghan, N.R., Balanos, G.M., 2010. Soft tissue artefact in the thoracic spine during axial rotation and arm elevation using ultrasound imaging: a descriptive study. Man. Ther. 15, 599–602. https://doi.org/10.1016/j.math.2010.05.004.

Heneghan, N.R., Rushton, A., 2016. Understanding why the thoracic region is the 'Cinderella' region of the spine. Man. Ther. 21, 274–276. https://doi.org/10.1016/j.math.2015.06.010.

Heneghan, N.R., Smith, R., Tyros, I., Falla, D., Rushton, A., 2018. Thoracic dysfunction in whiplash associated disorders: a systematic review. PLoS One 13, e0194235. https://doi.org/10.1371/journal.pone.0194235.
Hesby, B.B., Hartvigsen, J., Rasmussen, H., Kjaer, P., 2019. Electronic measures of movement impairment, repositioning, and posture in people with and without neck pain-a systematic review. Syst. Rev. 8, 220. https://doi.org/10.1186/s13643-019-1125-2.
Hogan, N., Sternad, D., 2009. Sensitivity of smoothness measures to movement duration, amplitude, and arrests. J. Mot. Behav. 41, 529–534. https://doi.org/10.3200/35-09-004-RC.
Johnson, K.D., Kim, K.M., Yu, B.K., Saliba, S.A., Grindstaff, T.L., 2012. Reliability of thoracic spine rotation range-of-motion measurements in healthy adults. J. Athl. Train. 47, 52–60. https://doi.org/10.4085/1062-6050-47.1.52.
Jørgensen, R., Ris, I., Juhl, C., Falla, D., Juul-Kristensen, B., 2017. Responsiveness of clinical tests for people with neck pain. BMC Muscoskel. Disord. 18, 548. https://doi.org/10.1186/s12891-017-1918-1.
Joshi, S., Balthillaya, G., Neelapala, Y.V.R., 2019. Thoracic posture and mobility in mechanical neck pain population: a review of the literature. Asian Spine J 13, 849–860. https://doi.org/10.31616/asj.2018.0302.
Keogh, J.W.L., Cox, A., Anderson, S., Liew, B., Olsen, A., Schram, B., Furness, J., 2019. Reliability and validity of clinically accessible smartphone applications to measure joint range of motion: a systematic review. PLoS One 14, e0215806. https://doi.org/10.1371/journal.pone.0215806.
Koo, T.K., Li, M.Y., 2016. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. Journal of Chiropractic Medicine 15, 155–163. https://doi.org/10.1016/j.jcm.2016.02.012.
Kottner, J., Audigé, L., Brorson, S., Donner, A., Gajewski, B.J., Hróbjartsson, A., Roberts, C., Shoukri, M., Streiner, D.L., 2011. Guidelines for reporting reliability and agreement studies (GRRAS) were proposed. J. Clin. Epidemiol. 64, 96–106. https://doi.org/10.1016/j.jclinepi.2010.03.002.
Lu, M.J., Zhong, W.H., Liu, Y.X., Miao, H.Z., Li, Y.C., Ji, M.H., 2016. Sample size for assessing agreement between two methods of measurement by bland-altman method. Int. J. Biostat. 12 https://doi.org/10.1515/ijb-2015-0039.
Moghaddas, D., de Zoete, R.M.J., Edwards, S., Snodgrass, S.J., 2019. Differences in the kinematics of the cervical and thoracic spine during functional movement in individuals with or without chronic neck pain: a systematic review. Physiotherapy 105, 421–433. https://doi.org/10.1016/j.physio.2019.01.007.
Moghaddas, D., Edwards, S., Snodgrass, S.J., 2022. Comparisons of cervical and thoracic spine kinematic joint and body segment angles, timing, and velocity between individuals with and without chronic idiopathic neck pain during functional tasks. Gait Posture 92, 394–400. https://doi.org/10.1016/j.gaitpost.2021.12.005.
Morita, D., Yukawa, Y., Nakashima, H., Ito, K., Yoshida, G., Machino, M., Kanbara, S., Iwase, T., Kato, F., 2014. Range of motion of thoracic spine in sagittal plane. Eur. Spine J. 23, 673–678. https://doi.org/10.1007/s00586-013-3088-7.
NDI, 2017. Northern digital Inc: Optotrak certus. Retrieved from. http://www.ndigital.com/msci/products/optotrak-certus.
Özer Kaya, D., Çelenay Ş, Toprak, 2017. An investigation of sagittal thoracic spinal curvature and mobility in subjects with and without chronic neck pain: cut-off points and pain relationship. Turk. J. Med. Sci. 47, 891–896. https://doi.org/10.3906/sag-1605-178.
Palsson, T.S., Christensen, S.W., Thomsen, M.H., Hirata, R.P., 2019. Assessment of range and quality of neck movement using a smartphone-based application. Musculoskelet Sci Pract 41, 64–69. https://doi.org/10.1016/j.msksp.2019.01.002.
Papi, E., Koh, W.S., McGregor, A.H., 2017. Wearable technology for spine movement assessment: a systematic review. J. Biomech. 64, 186–197. https://doi.org/10.1016/j.jbiomech.2017.09.037.
Poitras, I., Dupuis, F., Bielmann, M., Campeau-Lecours, A., Mercier, C., Bouyer, L.J., Roy, J.S., 2019. Validity and reliability of wearable sensors for joint angle estimation: a systematic review. Sensors 19. https://doi.org/10.3390/s19071555.
Rattanakoch, J., Samala, M., Limroongreungrat, W., Guerra, G., Tharawadeepimuk, K., Nanbancha, A., Niamsang, W., Kerdsomnuek, P., Suwanmana, S., 2023. Validity and reliability of inertial measurement unit (IMU)-Derived 3D joint kinematics in persons wearing transtibial prosthesis. Sensors 23. https://doi.org/10.3390/s23031738.
Sjölander, P., Michaelson, P., Jaric, S., Djupsjöbacka, M., 2008. Sensorimotor disturbances in chronic neck pain–range of motion, peak velocity, smoothness of movement, and repositioning acuity. Man. Ther. 13, 122–131. https://doi.org/10.1016/j.math.2006.10.002.
Stenneberg, M.S., Rood, M., de Bie, R., Schmitt, M.A., Cattrysse, E., Scholten-Peeters, G. G., 2017. To what degree does active cervical range of motion differ between patients with neck pain, patients with whiplash, and those without neck pain? A systematic review and meta-analysis. Arch. Phys. Med. Rehabil. 98, 1407–1434. https://doi.org/10.1016/j.apmr.2016.10.003.
Takatalo, J., Ylinen, J., Pienimäki, T., Häkkinen, A., 2020. Intra- and inter-rater reliability of thoracic spine mobility and posture assessments in subjects with thoracic spine pain. BMC Muscoskel. Disord. 21, 529. https://doi.org/10.1186/s12891-020-03551-4.
Teufl, W., Miezal, M., Taetz, B., Frohlich, M., Bleser, G., 2019. Validity of inertial sensor based 3D joint kinematics of static and dynamic sport and physiotherapy specific movements. PLoS One 14, e0213064. https://doi.org/10.1371/journal.pone.0213064.
The National Committee on Health Research Ethics, 2019. What to notify?, 21. Februrary 2021. https://en.nvk.dk/how-to-notify/what-to-notify.
Thoomes-de Graaf, M., Thoomes, E., Fernández-de-Las-Peñas, C., Plaza-Manzano, G., Cleland, J.A., 2020. Normative values of cervical range of motion for both children and adults: a systematic review. Musculoskelet Sci Pract 49, 102182. https://doi.org/10.1016/j.msksp.2020.102182.
Treleaven, J., Takasaki, H., Grip, H., 2019. Altered trunk head co-ordination in those with persistent neck pain. Musculoskelet Sci Pract 39, 45–50. https://doi.org/10.1016/j.msksp.2018.11.010.
Tsang, S.M., Szeto, G.P., Lee, R.Y., 2014. Altered spinal kinematics and muscle recruitment pattern of the cervical and thoracic spine in people with chronic neck pain during functional task. J. Electromyogr. Kinesiol. 24, 104–113. https://doi.org/10.1016/j.jelekin.2013.10.011.
Tsigilis, N., Theodosiou, A., 2008. The influence of multiple administration of a psychomotor test on performance and learning. J. Strength Condit Res. 22, 1964–1968. https://doi.org/10.1519/JSC.0b013e3181821b75.
Vernon, H., 2008. The neck disability Index: state-of-the-art, 1991-2008. J. Manip. Physiol. Ther. 31, 491–502. https://doi.org/10.1016/j.jmpt.2008.08.006.
von Elm, E., Altman, D.G., Egger, M., Pocock, S.J., Gøtzsche, P.C., Vandenbroucke, J.P., 2007. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. Lancet 370, 1453–1457. https://doi.org/10.1016/s0140-6736(07)61602-x.
Weigl, M., Letzel, J., Angst, F., 2021. Prognostic factors for the improvement of pain and disability following multidisciplinary rehabilitation in patients with chronic neck pain. BMC Muscoskel. Disord. 22, 330. https://doi.org/10.1186/s12891-021-04194-9.
Yan, J.H., Hinrichs, R.N., Payne, V.G., Thomas, J.R., 2000. Normalized jerk: a measure to capture developmental characteristics of young girls' overarm throwing. J. Appl. Biomech. 16, 196–203. https://doi.org/10.1123/jab.16.2.196.