DYSKIMOT: An ultra-low-cost inertial sensor to assess head's rotational kinematics in adults during the Didren-Laser Test

Renaud Hage [1,2,*], Christine Detrembleur [1], Frédéric Dierick [2,3], Laurent Pitance [1], Laurent Jojczyk[2], Wesley Estievenart[2] and Fabien Buisseret [2,4]

[1] Laboratoire NMSK, Institut de Recherche Expérimentale et Clinique, Université catholique de Louvain, Brussels, Belgium;
[2] CeREF, Chaussée de Binche 159, 7000 Mons, Belgium;
[3] Centre National de Rééducation Fonctionnelle et de Réadaptation – Rehazenter, Laboratoire d'Analyse du Mouvement et de la Posture (LAMP), Luxembourg, Grand-Duché du Luxembourg;
[4] Service de Physique Nucléaire et Subnucléaire, UMONS, Research Institute for Complex Systems, 20 Place du Parc, 7000 Mons, Belgium.

* Correspondence renaudhage@gmail.com

Abstract: Various noninvasive measurement devices can be used to assess cervical motion. Size, complexity and cost of gold-standard systems make them not suited in clinical practice, and actually difficult to use outside dedicated laboratory. Nowadays, ultra-low-cost inertial measurement units are available but without any packaging nor user-friendly interface. DYSKIMOT is a home-designed, small-sized, motion sensor based on the latter technology, aiming at being used by clinicians in "real-life situations". In the present study. DYSKIMOT was compared with a gold-standard optoelectronic system (Elite). Our goal was to evaluate the accuracy of DYSKIMOT in assessing the kinematics in fast head rotations. Kinematics was simultaneously recorded by the DYSKIMOT and Elite systems during the execution of the DidRen Laser test and performed by 15 participants and 9 patients. Kinematic variables were computed from the position, speed and acceleration time series. Two-way ANOVA, Passing-Bablok regressions and Dynamic Time Warping analysis showed good to excellent agreement between Elite and DYSKIMOT, both at the qualitative level of the time series shape and at the quantitative level of peculiar kinematical events' measured values. In conclusion, DYSKIMOT sensor is as relevant as a gold-standard system to assess kinematical features during fast head rotations in participants and patients, demonstrating its usefulness in clinical practice or research in ecological environment.

Keywords: inertial sensor; kinematics; head rotation; ecological research

1. Introduction

Neck pain is a frequent neuromusculoskeletal symptom with a prevalence ranging from 22 to 70%, increasing with age and most common in women around 50 years old [1]. As it is the fourth one leading cause of years lived with disability in 188 countries during the period 1990-2013, as concluded in Vos et al. [2], the correct identification of the etiology of neck pain is therefore a societal issue. However, probably due to imperfect diagnosis, majority of neck pain are still nowadays called "non-specific" [3].

According to the Bayesian inference by which the probabilities of various hypothetical causes are calculated from the observation of known events, a medical diagnosis indicates that one disorder (eg. muscular, discogenic, lack of sensorimotor control, ...) more than another is probably the cause of a patient's symptoms, and thus, need investigations to reinforce or refute this [4]. This way of thinking leads us to believe that appropriate diagnostic and the resulting therapeutic pass through investigations of the data analysis of the quantitative (strength and range of motion) and the qualitative (sensorimotor appraisal) assessment of the neck [5-8]. As a result, clinicians are showing increasing interest in systems that can monitor movements, with the hope of better defining their patients' clinical picture by focusing on head motion [8-10].

Various noninvasive three-dimensional motion capture systems are used in the field of cervical research in order to evaluate kinematic variables going beyond simple range of motion such as speed, acceleration and deceleration : electrogoniometers [5], ultrasound waves [11], optical-based systems [12, 13] and inertial sensors [14] and so on. Nevertheless, their dimension, complexity and cost make such systems often difficult to use outside dedicated laboratory. The need for compact, user-friendly and low-cost measurement devices that can bring relevant information in everyday clinical practice is therefore obvious and goes beyond neck exploration, although we chose to focus on that topic in the present study.

Inertial sensors (IMUs) began to be applied to human movement study before 2000 [15]. IMUs consist at least of accelerometers and gyroscopes which are generally organized in orthogonal triads in order to obtain a three-dimensional measurement [16]. Most often, IMUs are supplemented by magnetometers and thermometers. This technology has the advantage of not requiring external equipment such as cameras to get the orientation and position of the human segments, and it does not limit the subject's movement to the volume covered by the cameras. IMUs thus seem then to be the appropriate basic tool to design a device which could be easily used in a clinical and ecological environment [17, 18]. Note that this technology suffers of high measurements noise and drift [19] that can mostly be cured by a Kalman filter [19]. Nowadays, large-scale production of IMUs sensors make them affordable compared to gold-standard systems but nevertheless the prices are several thousand euros (e.g. Vicon®, XSENS®). Other IMUs may indeed be bought at typical prices less than 50€, still without any packaging nor user-friendly interface.

It is in this context that our team designed a small-sized, light, and ultra-low-cost inertial sensor called DYSKIMOT. After first tests in laboratory, our goal was to evaluate the accuracy of DYSKIMOT compared with a gold-standard optoelectronic system when performing a clinical sensorimotor test developed by Hage et al. (i.e. the DidRen-Laser Test) in small groups of participants and neck pain patients [20]. According to the literature, we selected different dynamic outcomes to evaluate our DYSKIMOT [21, 22]: range of motion, peak speed, average speed, peak acceleration and peak deceleration.

2. Materials and Methods

2.1. Participants

Fifteen cervical non-disabled participants (NDP) (3 females, 12 males) and 9 cervical disabled patients (DP) (4 females, 5 males) were recruited from students in University hospital and among researchers' patients to participate in this study, see Table 1. Inclusion criteria for NDP were the absence of neck pain episodes in the last 6 months and a Neck Disability Index (NDI) [23] score of less than or equal to 8%. Inclusion criteria for the DP were a numeric pain rating scale (NPRS) equal to or greater than 3/10 [24] and an NDI >8%. Exclusion criteria were for NDP and DP: impaired cognition, blindness, deafness, dizziness or vestibular disorders diagnosed by a physician. Participants and patients did not exhibit any neuromusculoskeletal or neurologic disorder that could influence the performance of head rotation in the horizontal plane. The participants signed informed consent. The individuals in this manuscript have given written informed consent to publish their case details. The study was approved by the local ethics committee (Comité d'Ethique Hospitalo-Facultaire Saint-Luc-UCL (IRB 00001530)) and conducted in accordance with the declaration of Helsinki.

Table 1. Characteristics of the participants in NDP and DP groups. Data are given either under mean±SD or median [Q1-Q3] form.

	NDP (n=15)	DP (n=9)
Age (years)	24±3	53±7
Gender (men/women)	12/3	5/4
BMI (kg/m^2)	22.2±2.7	21.8±2.3
NDI (%)	0 [0-0]	14 [10-16]
NPRS (/10)	0 [0-0]	3 [0-0][1]

[1] SD = Standard Deviation, BMI = Body Mass Index, Q1 = First Quartile, Q3 = Third Quartile, NDI = Neck Disability Index. NPRS = Numeric Pain Rating Scale, NDP = Non-Disabled Participants. DP = disabled participants.

2.2. The DidRen Laser Test

The DidRen Laser Test [20] was used to assess neck mobility through standardized axial rotations of the head in NDP and DP. After having watched an explanatory video, the participant sited on a chair with backrest, without armrests, placed at 90 cm from a vertical panel equipped with 3 targets (LEDs) arranged horizontally and located 52 cm apart (Figure 1). An adjustable helmet with a laser beam attached on the top was worn by the participant (Figure 2). The experimenter (RH) adjusted the helmet so that the laser hit the central target while the participant was in a neutral position before the test begins. The instructions were the same for all participants: "You must reach the targets as fast as you can and perform the head movement without moving your shoulders". The targets were then turned on in a predefined sequence and the participant's task is to rotate his/her head so that the laser beam hit the target as quickly as possible. We must specify that when the laser beam was stabilized by the participant on a target for at least 0.5 s the target LED let up and an audible signal was emitted. A complete test was composed of 5 cycles of cervical axial rotation to the right and left sides respectively. A first test was carried out to familiarize the participant and a second for data recording and analyses [20].

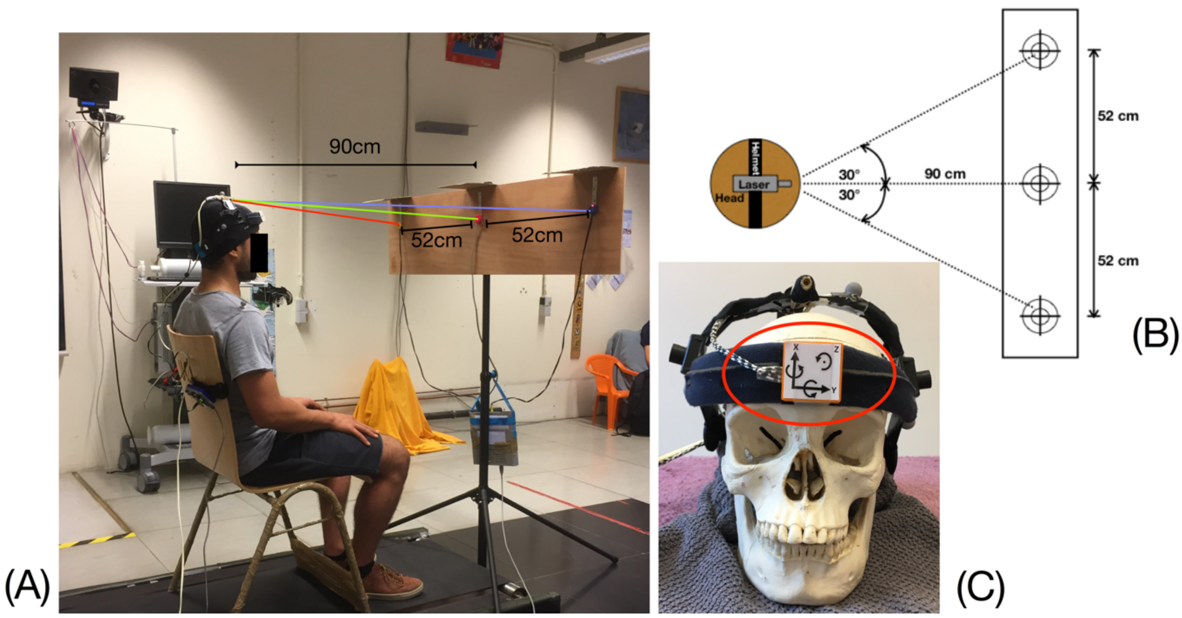


Figure 1. (A) DidRen Laser Test installation device. (B) Schematic view from above. The passage from one target to another induces an axial rotation of the head of 30° either to the left or to the right sides of the bodyline. (C) The Helmet worn by the participant with the Laser on the top. The DYSKIMOT sensor can be seen (red circle) at the front of the helmet.

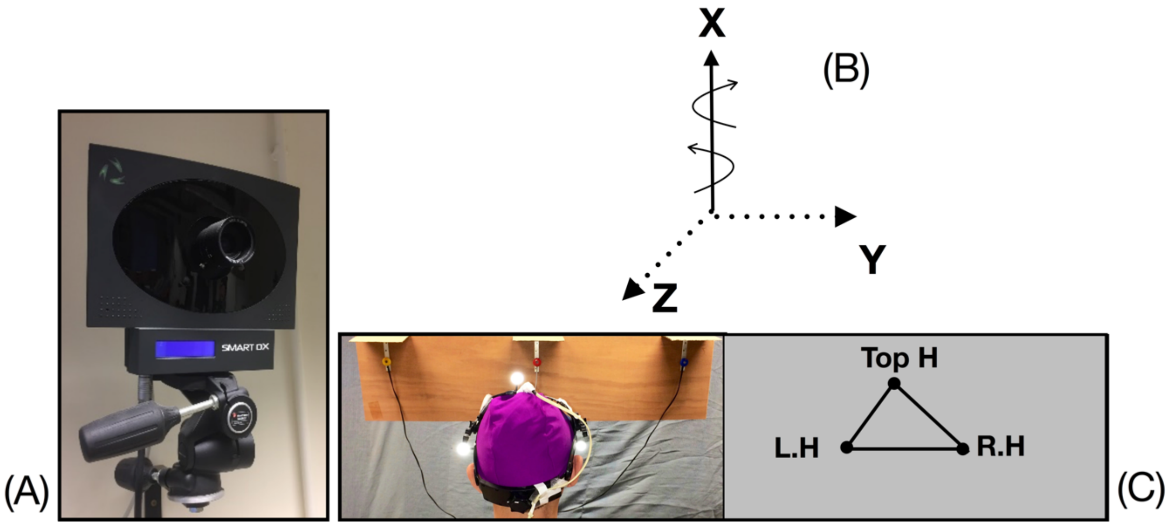


Figure 2. (A) Infra-red cameras (ELITE, BTS, Milan, Italy). (B) Head axis of rotation is denoted as X. (C) Placement of the reflective markers on the head.

2.3. Motion sensors

2.3.1. Elite system (BTS)

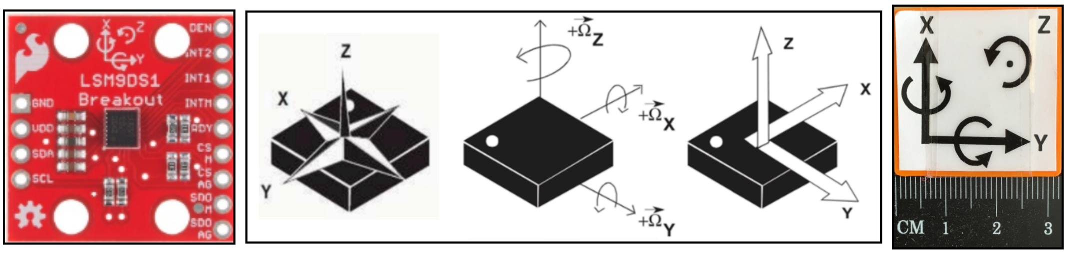
An optoelectronic system composed by 8 infra-red cameras (ELITE, BTS, Milan, Italy) (Figure 3 A) with sampling frequency of $\bar{f}$ = 200 Hz test carried out the three-dimensional recording of the markers on the helmet during the DidRen Laser. A kinematic model composed of 3 markers on a helmet and fixed during all experimentations representing the head was used and adapted from [25] (Figure 2 C and D). Helmet markers were positioned such that one was just aside the top of the head (Top H) and positioned next to the laser, and two on each side of the head (R.H and L.H) (Figure 2 C). Coordinate system is such that the axis of rotation for axial rotations of the head is X (Figure 2 B). The movement occurred around the global coordinate system. The system was previously calibrated within the infra-red camera's field of view [25].

Angular displacement time series of the head, $\bar{\theta}_i$, has been computed from the coordinates of the markers as described in details in [26]. The angular velocity was computed as $\bar{\omega}_i = \frac{\bar{\theta}_{i+n}-\bar{\theta}_{i-n}}{2 .n.\Delta\bar{t}}$, with n=5 and $\Delta\bar{t}$ =1/$\bar{f}$ and, similarly, the angular acceleration as been computed as $\bar{\alpha}_i = \frac{\bar{\omega}_{i+n}-\bar{\omega}_{i-n}}{2 .n.\Delta\bar{t}}$.

2.3.2. DYSKIMOT

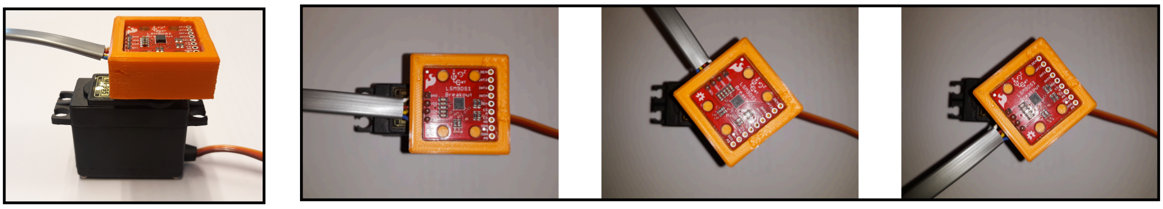
The DYSKIMOT sensor is based on the MEMS IMU LSM9DS1 (SparkFun), its weight is 10.44 gr and its size is 3x3 cm (Figure 3 A and C). It is composed of 3-axis accelerometer, gyrometer and magnetometer, plus a temperature sensor (Figure 3 B). These internal components respectively measure acceleration (in[g], ±16[g]), angular velocity (in[°/s], ±2000[°/s]) and magnetic field (in[gauss], ±16[gauss]). It works between -40°C and + 85°C and the sensitivity depends on the sensor and the selected range (i.e: 0.061mg/LSB with accelerometer at ± 2g). Communication with other electronic components is made via SPI or I2C protocol. The data recorded at a sampling frequency f = 100 Hz are transmitted to a PC via an Arduino Uno Rev 3 and a USB cable (RS232 serial link). The Arduino contains the data recovery program, using the SparkFun library provided for this sensor, and transfers them to a home-made acquisition software.

The DYSKIMOT sensor has been placed in front of the helmet (Figure 1 C), which is the most reliable position to record cervical axial rotation [6]. The X-component of angular velocity measured by the gyroscope is recorded, i.e. the time series ω_i . A trapezoidal integration gives the head's rotation angles θ_i while the derivative $\alpha_i = \frac{\omega_{i+n} - \omega_{i-n}}{2.n.\Delta t}$ with n=5 and Δt =1/f gives the head's angular acceleration. Angles computed from the gyroscope show a linear drift. Since the DidRen Laser Test consists in quasi-periodic rotations of 30° around a neutral position, an straightforward way of removing the drift is to subtract the least square regression line from the time series θ_i. Notice that Elite (DYSKIMOT) time series are written with (without) a bar.



(A) (B) (C)

Figure 3. (A) Micro Electro-Mechanical Systems (MEMS). (B) 3-axis accelerometer, a 3-axis gyrometer, a 3-axis magnetometer and a temperature sensor. (C) Dimension of the DYSKIMOT.



(A) (B) (C) (D)

Figure 4. (A) Servo motor + housing adapted to its axis to fix an IMU. (B). Angle = 0°, (C). Angle = +30°, (D). Angle = -30°.

Before using the DYSKIMOT in this study, a test was performed using a sensor attached to a servo motor (see Figure 4) to mimic the sequence of the cervical axial rotation during the DidRen test, i.e. angles from 30° to the left and right by going back through the 0 angle (Figure 4). The servo motor with an Arduino Uno Rev 3, has been programmed to perform the sequence repeatedly. The result can be seen in Figure 5. The sensor is kept static duting the first 20 s of the test. The linear drift is clearly observable on the raw angular data and the parameters of this line are computed by a least squares regression. Then comes the activation of the actuator and the beginning of the sequence (around 25 s). The fitted linear drift is eventually subtracted from the raw angular data. As it can be observed in Figure 5, such a procedure is satisfactory for time series having the typical behavior of the DidRen Laser Test. Such a procedure may actually work in all cases, including non-perriodic tests. The regressin line parameters may even be stored provided they do not change over time or with temperature.

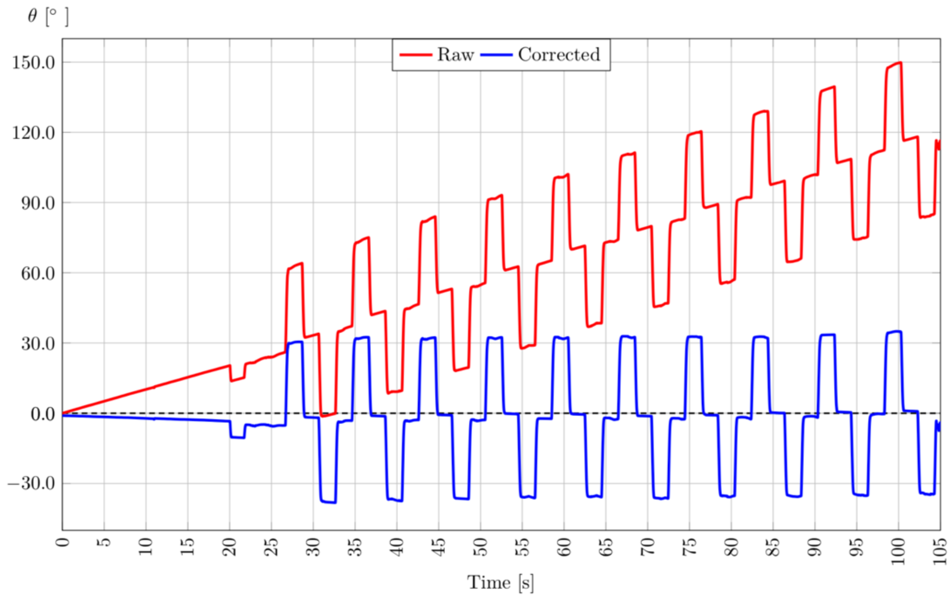


Figure 5. Example of linear drift due to integration of DYSKIMOT's raw angular velocity (red line) and correction of the drift of the test angle Z with the servo motor (blue line). The corrected angle (blue line) is obtained by subtraction of the regression line to the raw angle. This plot has been obtained by fixing the DYSKIMOT sensor on a servo motor (MG995, Tower Pro) performing successive and opposite rotations of amplitude 30°.

2.4. Data analysis

The following parameters were computed from the available time series $\bar{\theta}, \bar{\omega}, \bar{\alpha}$ (Elite) and θ, ω, α (DYSKIMOT) (Figure 6): (1) angle (range of motion, in °); (2) peak angular velocity (maximum angular velocity reached, in $°s^{-1}$); average angular velocity (in $°s^{-1}$); (3) peak angular acceleration (maximum angular acceleration reached, in $°s^{-2}$); (4) peak angular deceleration (minimum angular acceleration reached, in $°s^{-2}$). All parameters were calculated during each cycle and averaged on the 5 cycles achieved by each participant, see Figures 6 and 7 for a graphical illustration of our computational procedure. Although our goal is to characterize the agreement between Elite and DYSKIMOT sensors for ND and NDP participants, it is worth saying at this stage that the computed parameters are of clinical interest. As showed in [9,10] for example, neck velocity during fast rotation has sensibility and specificity to discriminate between nonspecific neck pain and healthy control people.

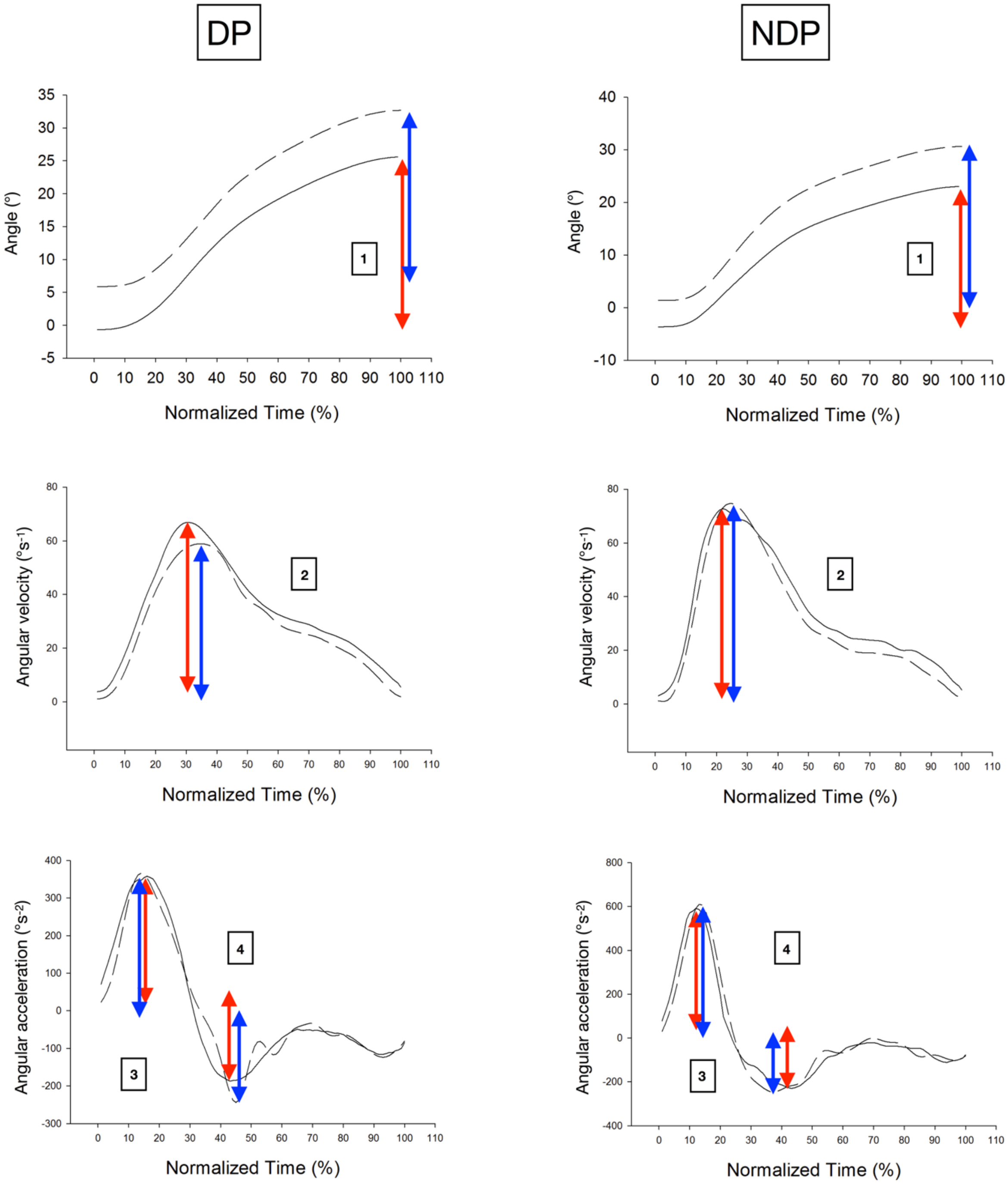


Figure 6. Typical plots of variables analyzed during one right rotation in a DP (34 yrs, Male, NDI = 22, NRPS= 5) and an NDP (25 yrs, Male, NDI = 0, NPRS = 0). Elite curves (dotted lines) can be compared to DYSKIMOT ones (solid lines). Computed parameters are illustrated by blue (Elite) or red (DYSKIMOT) arrows. (1) angle; (2) peak angular velocity; (3) peak angular acceleration; (4) peak angular deceleration.

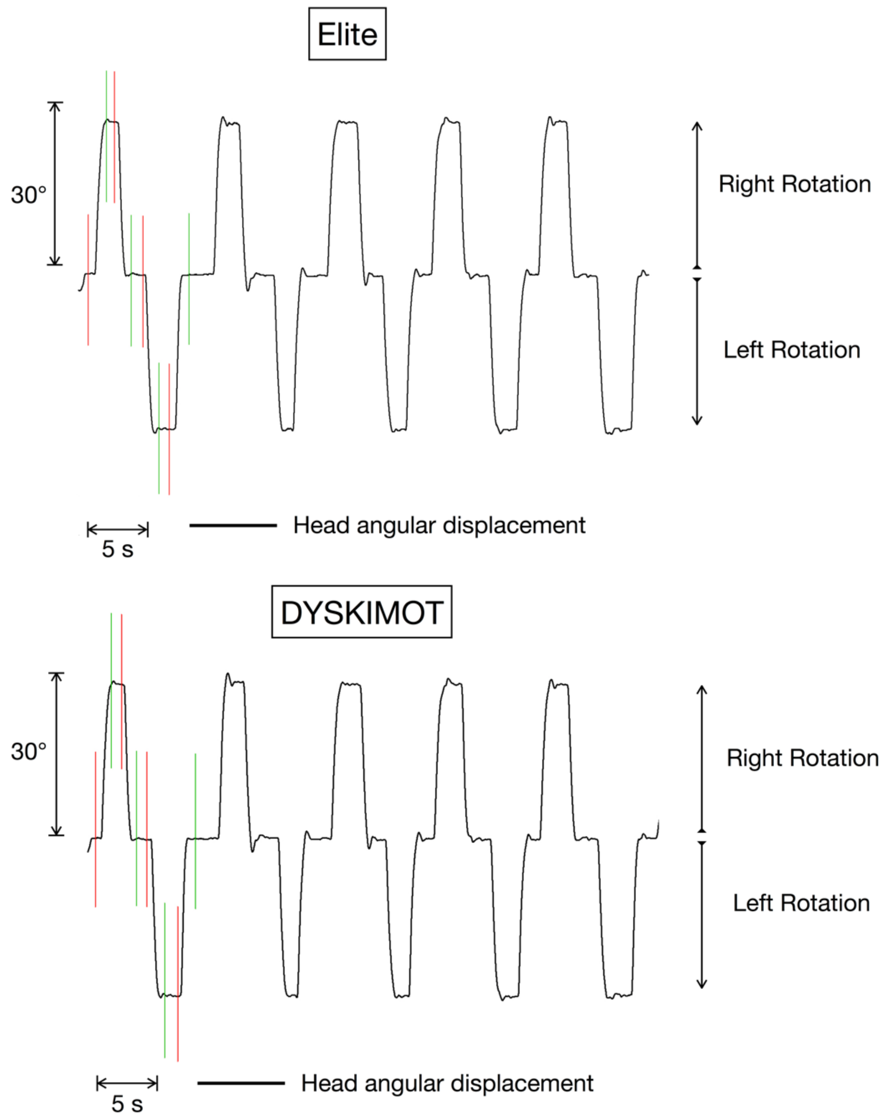


Figure 7. Comparison of an example of Elite and DYSKIMOT typical traces of the head motion during the 5 cycles of the DidRen Laser Test in an DP (51 yrs, female, NDI=14, NPRS=3). Cursors indicating the beginning (red) and end (green) of one rotation movement are shown.

A Passing-Bablok regression of the DYSKIMOT vs Elite results was performed on the individual values of the parameters for DP and NDP simultaneously so that the agreement between both sensors can be appraised and summarized by a “calibration line”.

A two-way ANOVA was then used to assess potential differences between the two systems (System factor: Elite or DYSKIMOT) and between the groups (Status factor: NDP or DP) for the parameters mentioned above. When the ANOVA indicated significant interaction, a *post hoc* Holm-Sidak analysis with pairwise multiple comparisons was carried out. Significance was fixed at $p<0.05$ and all statistical procedures were performed with SigmaPlot 13 (Systat Software, Inc).

Finally, a dynamic time warping (DTW) analysis (without windowing) was carried on the z-normalized data and the Euclidian DTW distances between the time series angle $(\theta, \bar{\theta})$, angular velocity $(\omega, \bar{\omega})$, angular acceleration $(\alpha, \bar{\alpha})$ for DYSKIMOT and Elite were calculated for all the participants and then averaged. Recall that the z-normalization consists in replacing a time series X by $\frac{X-E(X)}{SD(X)}$, E and SD denoting the average and standard deviation respectively.

The Passing-Bablok regressions and the DTW were performed by using R v3.4.2 and the packages mcr and dtw.

3. Results

A total of twenty four participants were recruited; the main features of our population are listed in Table 1.

Results of the two-way ANOVA are shown in Table 2. A statistically significant difference was observed in the angle ($p<0.001$) and average angular velocity (0.022) for the System factor, i.e. Elite and DYSKIMOT lead to different means. Neither the Status factor nor the interaction effects lead to statistically significant differences.

Table 2. Results of the two-way ANOVA performed on the parameters. p values are given for the differences between Elite and DYSKIMOT (System), between DP and NDP (Status) and for the interaction effect System x Status. p values lower than 0.05 are given in bold font.

	ANOVA	Difference of the means (Dyskimot-Elite or DP-NDP)	p
Angle (°)	System	1.76	<0.001
	Status	-0.398	0.157
	System x Status		0.094
Average angular velocity (°s^{-1})	System	-5.50	0.022
	Status	1.72	0.462
	System x Status		0.655
Peak angular velocity (°s^{-1})	System	5.74	0.498
	Status	6.22	0.630
	System x Status		0.708
Peak angular acceleration (°s^{-2})	System	89.9	0.282
	Status	59.8	0.473
	System x Status		0.880
Peak angular deceleration (°s^{-2})	System	-81.3	0.261
	Status	-46.6	0.517
	System x Status		0.955

Table 3. Results of the two-way ANOVA performed on the parameters. p values are given for the differences between Elite and DYSKIMOT (System), between DP and NDP (Status) and for the interaction effect System x Status. p values lower than 0.05 are given in bold font.

	Slope	Offset	r
Angle (°)	0.908 [-2.09, 1.86]	4.34 [-20.6, 82.5]	0.431
Average angular velocity (°s^{-1})	0.922 [0.713, 1.32]	-0.518 [-18.0, 7.57]	0.694
Peak angular velocity (°s^{-1})	1.01 [0.942, 1.11]	2.80 [-5.27, 10.2]	0.906
Peak angular acceleration (°s^{-2})	1.10 [0.939, 1.20]	7.71 [-50.4, 125]	0.922
Peak angular deceleration (°s^{-2})	1.04 [0.906, 1.13]	43.1 [-0.623, 131]	0.918

Results of Passing-Bablok regressions are shown in Table 3. The slopes were close to 1, the best agreement being observed for the peak angular velocity, and Pearson's coefficients range from 0.431 to 0.922, i.e. moderate to excellent linear correlation between DYSKIMOT and Elite results. The agreement between both systems can be graphically appraised in Figure 8.

The DTW distance (d) allows for an estimation of the closeness of DYSKIMOT and Elite systems for the whole time series, not only for selected valued. We obtained 5.16±2.68, 8.82±5.80 and 14.40 ±7.14 for angle, angular velocity and angular acceleration time series respectively. Typical traces are shown in Figure 9.

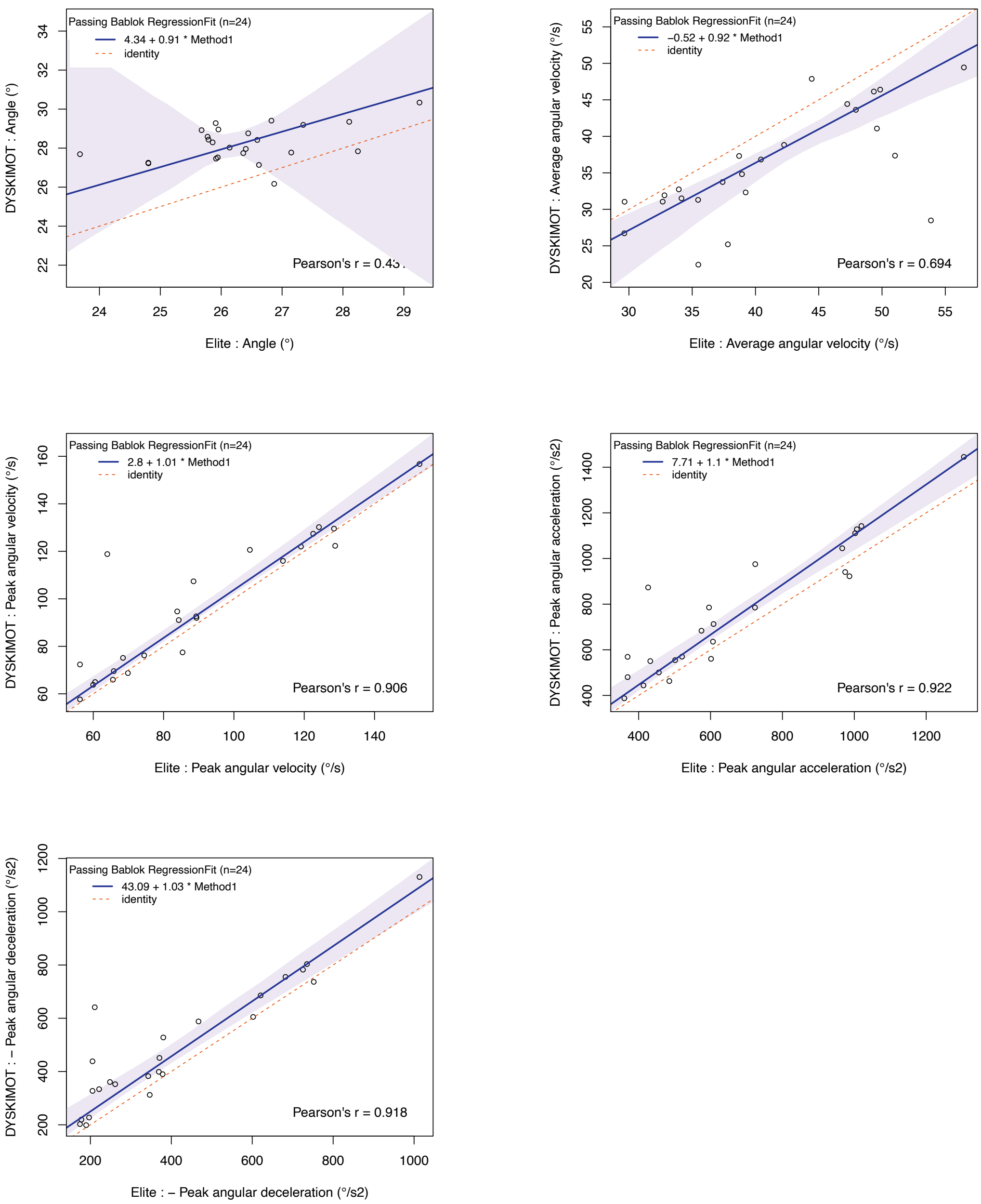


Figure 8. Passing-Bablok regressions showing the individual parameters computed from the DYSKIMOT and Elite data (points). The regression line (solid line) is given and compared to the identity line (dotted line). The 95% confidence interval for the linear fit is also displayed (colored band).

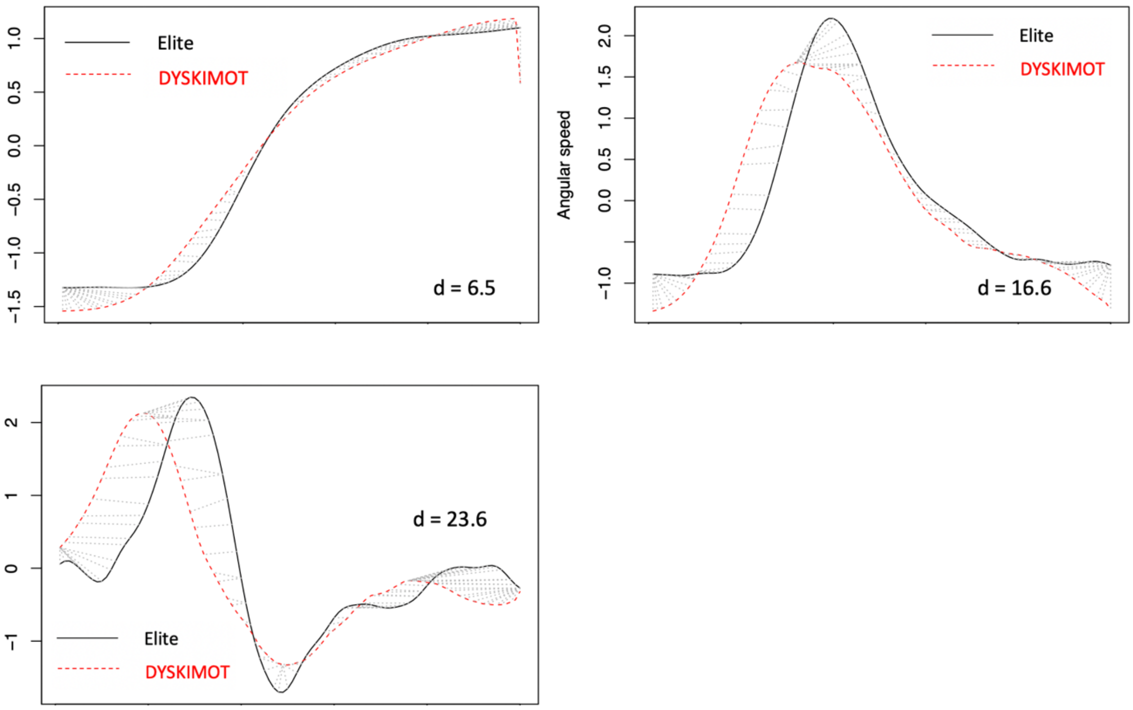


Figure 9. Typical plots of DTW matching between Elite (black solid lines) and IMU (red dashed lines) analyzed for z-normalized in one NDP (22 yrs, Male, NDI = 0, NRPS= 0) participant. The DTW distance is added for completeness.

4. Discussion

The two-way ANOVA revealed that angle and average angular velocity were significantly different between the two systems. The difference in angle (1.76°) which is probably due to our "naïve" drift removal is nevertheless lower than the standard clinical angle evaluation via classical goniometry: An accuracy of 5° is reported [27], even more than the mean difference obtained between Elite and DYSKIMOT angle. Such significant difference observed between the two systems is not relevant, as specified by Cuesta-Vargas et al. [28], showing that an error of 2° is acceptable in most clinical situations. Concerning the average angular velocity, the difference of -5.50 $°s^{-1}$ may come from the errors induced by the derivation of the Elite position. Fortunately, this result is lower than the difference necessary to reveal significant difference (7.1 $°s^{-1}$) between adults and children [22]. Nevertheless, the clinical significance of a such difference is still not known. Apart from these differences, two other ANOVA results may be noted. First, as in [29], no significant difference between DP and NDP were observed for all variables studied. Second, the interactions effects (System x Status) do not induce significant differences. Hence DYSKIMOT and Elite systems are equally able (or unable) to assess DP and NDP from the parameters computed.

Many articles used Bland and Altman's method to evaluate the agreement between two measurements of the same magnitude [30, 31, 32]. As this method does not give any quantified results on the comparison and leaves the user to decide whether this agreement is clinically acceptable or not, we preferred to analyze the agreement between DYSKIMOT and Elite by resorting to Passing-Bablok regressions [33, 34]. The Passing-Bablok regression method is a non-parametric method for estimating the slope and the intercept of the linear relationship between two compared measures [34]. These two parameters are valued by medians and have the benefit of being less sensitive to extreme data and not making assumptions about the distribution of errors [33]. In our results, the Passing-Bablok lets appear that the link between same parameters computed from both systems is well compatible with a linear shape (r = 0.694 to 0.922) for all parameters but angle, for which Pearson's coefficient is rather weak (r = 0.431) [35]. Nonzero offsets are observed but the 95% confidence intervals are large and always contain 0 value, while the slope are close to 1 (up to 10% accuracy) with 95% confidence intervals always containing the value 1. Assuming that Elite results are gold-standard values, the Passing-Bablok regressions could be used to re-calibrate the DYSKIMOT data so that values get closer to the Elite ones.

Although DTW has been known in the field of acoustic signal comparison [36], it has also been proposed for the purposes of similarity analyze during functional pattern of gait [37] but never to compare motion neck signals obtained by two different devices. DTW is, by definition, sensitive for measuring two sequences with different lengths using dynamic programming [38]. In this work, the DTW distance between Elite and DYSKIMOT curves was adopted as an indicator of the similarity (up to an affine transformation) between the curves. In other words, the question was: Do both systems measures the same qualitative behaviors in position, angular velocity and angular acceleration? Although the angle is in poor agreement between both systems, the DTW distance between DYSKIMOT and Elite angle is minimal: This result is expected since the structure of angle is well simpler than angular velocity and angular acceleration. The DTW distance then increases between the angular velocity and the angular acceleration of the DYSKIMOT and Elite systems. This mostly results in the noise induced by the successive derivations, showing that qualitative features of these curves, especially the angular acceleration, should be interpreted carefully and might be artefacts of the sensor used.

The identification of particular kinematic events is relevant for clinical assessment of patients, but the global shape of time series may contain more information of clinical interest. In our case for example, it is known that neck pain patients have poorer sensory-motor control with open eyes, characterized by an increase in joint positioning error and a decrease in speed and acceleration during all movements [39]. The absence of difference in our kinematics data between patients and participants could seem unexpected as previous studies showed significant differences in terms of kinematics [8, 40]. However this absence of difference could be explained by our sample size, which was probably not large enough to be able to give this kind of result, and by the difficulty for the DidRen laser to discriminate between such groups [41, 42].

An obvious limitation of the present study is that we restricted our comparison of Elite and DYSKIMOT to cervical movements, while potential clinical applications may involve any other joints. Another limitation lies in the fact that we used "naïve" drift correction posteriorly to data acquisitions and must be implemented in real-time in the software. Moreover, the software is perfectible in the goal of clinical use.

We can conclude from the DidRen Laser Test that DYSKIMOT- based analysis compares fairly well to a gold-standard system up to linear errors. That ultra-low-cost sensor may thus bring reliable information to the clinician in real-life situations.

Funding & Acknowledgements: CeREF acknowledges financial support from the First Haute-Ecole programme, project n◦ 1610401, DYSKIMOT, in partnership with OMT-Skills (http://omtskills.be/), and financial support from the European Regional Development Fund through the Interreg FWVl programme (NOMADe project). We also thank Stanley Lognoul and Alexandre Simeoni for their help in taking the measurements.

References

1. Blanpied, P.R.; Gross, A.R.; Elliott, J.M.; Devaney, L.L.; Clewley, D.; Walton, D.M.; Sparks, C., and Robertson, E.K. Neck Pain: Revision 2017. *J Orthop Sports Phys Ther* **2017**, *47*, A1-A83.
2. Vos, T. et al. Global, regional, and national incidence, prevalence, and years lived with disability for 301 acute and chronic diseases and injuries in 188 countries, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. *The Lancet* **2015**, *386*, 743-800.
3. Coulter, I.D.; Crawford, C.; Vernon, H.; Hurwitz, E.L.; Khorsan, R.; Booth, M.S.; and Herman, P.M. Manipulation and Mobilization for Treating Chronic Nonspecific Neck Pain: A Systematic Review and Meta-Analysis for an Appropriateness Panel. *Pain Physician* **2019**, *22*, E55-E70.
4. Bays, P.M.; Wolpert, D.M. Computational principles of sensorimotor control that minimize uncertainty and variability. *J Physiol.* **2007**, *578*, 387-96.
5. Dugailly, P.M.; De Santis, R.; Tits, M.; Sobczak, S.; Vigne, A.; Feipel, V. Head repositioning accuracy in patients with neck pain and asymptomatic subjects: concurrent validity, influence of motion speed, motion direction and target distance. *European spine journal* **2015**, *24*, 2885-91.
6. Theobald, P.S.; Jones, M.D.; Williams, J.M. Do inertial sensors represent a viable method to reliably measure cervical spine range of motion? *Manual therapy* **2012**, *17*, 92-6.
7. Falla, D.; O'Leary, S.; Fagan, A.; Jull, G. Recruitment of the deep cervical flexor muscles during a postural-correction exercise performed in sitting. *Manual therapy* **2007**, *12*, 139-43.
8. Roijezon, U.; Djupsjobacka, M.; Bjorklund, M.; Hager-Ross, C.; Grip, H.; Liebermann, D.G. Kinematics of fast cervical rotations in persons with chronic neck pain: a cross-sectional and reliability study. *BMC musculoskeletal disorders* **2010**, *11*, 222.
9. Roijezon, U.; Clark, N.C.; Treleaven, J. Proprioception in musculoskeletal rehabilitation. Part 1: Basic science and principles of assessment and clinical interventions. *Manual therapy* **2015**, *20*, 368-77.
10. Sarig Bahat, H.; Weiss, P.L.; Sprecher, E.; Krasovsky, A.; Laufer, Y. Do neck kinematics correlate with pain intensity, neck disability or with fear of motion? *Manual therapy* **2014**, *19*, 252-8.
11. Michiels, S. et al. Measurement of cervical sensorimotor control: the reliability of a continuous linear movement test. *Manual therapy* **2014**, *19*, 399-404.
12. Hage, R.; Dierick, F.; Roussel, N.; Pitance, L.; Detrembleur, C. Age-related kinematic performance should be considered during fast head-neck rotation target task in individuals aged from 8 to 85 years old. *PeerJ* **2019**, 7. doi: 10.7717/peerj.7095.
13. Nagai, T. et al. The Effect of Target Position on the Accuracy of Cervical-Spine-Rotation Active Joint-Position Sense. *Journal of sport rehabilitation* **2016**, *25*, 58-63.
14. Zhou, Y.; Loh, E.; Dickey, J.P.; Walton, D.M.; Trejos, A.L. Development of the circumduction metric for identification of cervical motion impairment. *Journal of Rehabilitation and Assistive Technologies Engineering* 2018, *5*. doi: 10.1177/2055668318777984.
15. Willemsen, A.T.; van Alste, J.A.; Boom, H.B. Real-time gait assessment utilizing a new way of accelerometry. *Journal of biomechanics* **1990**, *23*, 859-63
16. Picerno, P. 25 years of lower limb joint kinematics by using inertial and magnetic sensors: A review of methodological approaches. *Gait & posture* **2017**, *51*, 239-46.
17. Robert-Lachaine, X.; Mecheri, H.; Larue, C.; Plamondon, A. Validation of inertial measurement units with an optoelectronic system for whole-body motion analysis. *Med Biol Eng Comput* **2017**, *55*, 609-19.
18. Boissy, P. et al. Wireless inertial measurement unit with GPS (WIMU-GPS) - wearable monitoring platform for ecological assessment of lifespace and mobility in aging and disease. *Conference proceedings : Annual International Conference of the IEEE Engineering in Medicine and Biology Society IEEE Engineering in Medicine and Biology Society Annual Conference 2011* ***2011***, 5815-9.
19. Szczesna, A. et al. Inertial Motion Capture Costume Design Study. *Sensors (Basel)* **2017**, *17*, Epub 2017/03/18. doi: 10.3390/s17030612.
20. Hage, R.; Ancenay, E. Identification of a relationship between cervical spine function and rotational movement control. *Annals of physical and rehabilitation medicine* **2009**, *52*, 653-67.
21. Sarig Bahat, H.; Weiss, P.L.; Laufer, Y. The effect of neck pain on cervical kinematics, as assessed in a virtual environment. *Archives of physical medicine and rehabilitation*, **2010**, *91*, 1884-90.

22. Hage, R.; Buisseret, F.; Pitance, L.; Brismee, J.M.; Detrembleur, C.; Dierick, F. Head-neck rotational movements using DidRen laser test indicate children and seniors' lower performance. *PloS one* **2019**, *14*, e0219515.
23. Vernon, H.; Mior, S. The Neck Disability Index: a study of reliability and validity. *Journal of manipulative and physiological therapeutics* **1991**, *14*, 409-15.
24. Meisingset, I.; Stensdotter, A.K.; Woodhouse, A.; Vasseljen, O. Neck motion, motor control, pain and disability: A longitudinal study of associations in neck pain patients in physiotherapy treatment. *Manual therapy* **2016**, *22*, 94-100.
25. Bulgheroni, M.V.; Antonaci, F.; Ghirmai, S.; Sandrini, G.; Nappi, G.; Pedotti, A. A 3D kinematic method for evaluating voluntary movements of the cervical spine in humans. Functional neurology **1998**, *13*, 239-45.
26. Davis, R.B.; Õunpuu, S.; Tyburski, D.; Gage, J.R. A gait analysis data collection and reduction technique. *Human movement science* **1991**, *10*, 575-87.
27. Youdas, J.W.; Carey, J.R.; Garrett, T.R. Reliability of measurements of cervical spine range of motion--comparison of three methods. *Physical therapy* **1991**, *71*, 98-104.
28. Cuesta-Vargas, A.I.; Galan-Mercant, A.; Williams , J.M. The use of inertial sensors system for human motion analysis. *Physical therapy reviews : PTR* **2010**, *15*, 462-73.
29. Duc, C.; Salvia, P.; Lubansu, A., Feipel, V.; Aminian, K. A wearable inertial system to assess the cervical spine mobility: comparison with an optoelectronic-based motion capture evaluation. *Med Eng Phys* **2014**, *36*, 49-56.
30. Teufl, W.; Miezal, M.; Taetz, B.; Frohlich, M.; Bleser, G. Validity. Test-Retest Reliability and Long-Term Stability of Magnetometer Free Inertial Sensor Based 3D Joint Kinematics. *Sensors (Basel)* **2018**, *18*. Epub 2018/06/24.
31. Saber-Sheikh, K.; Bryant, E.C.; Glazzard, C.; Hamel, A.; Lee, R.Y. Feasibility of using inertial sensors to assess human movement. *Manual therapy* **2010**, *15*, 122-5. Epub 2009/07/28.
32. Bolink, S.A. et al. Validity of an inertial measurement unit to assess pelvic orientation angles during gait, sit-stand transfers and step-up transfers: Comparison with an optoelectronic motion capture system. *Med Eng Phys* **2016**, *38*, 225-31.
33. Fuhrman, C.; Chouaid, C. Concordance between two variables: numerical approaches (qualitative observations - the kappa coefficient-; quantitative measures. *Revue des maladies respiratoires* **2004**, *21*, 123-5.
34. Bilic-Zulle, L. Comparison of methods: Passing and Bablok regression. *Biochemia medica* **2011**, 21, 49-52.
35. Grenier, B.; Dubreuil, M.; Journois, D. Comparison of two measurement methods: the Bland and Altman assessment. *Annales francaises d'anesthesie et de reanimation* **2000**, *19*, 128-35.
36. Rosa, M.; Fugmann, E.; Pinto, G.; Nunes, M. An anchored dynamic time-warping for alignment and comparison of swallowing acoustic signals. *Conference proceedings : Annual International Conference of the IEEE Engineering in Medicine and Biology Society 2017* **2017**, 2749-52.
37. Lee, H.S. Application of dynamic time warping algorithm for pattern similarity of gait. *Journal of exercise rehabilitation* **2019**, *15*, 526-30.
38. Yang, C.Y.; Chen, P.Y.; Wen, T.J.; Jan, G.E. IMU Consensus Exception Detection with Dynamic Time Warping-A Comparative Approach. Sensors (Basel) 2019, 19, Epub 2019/05/17.
39. de Zoete, R.M.; Osmotherly, P.G.; Rivett, D.A.; Farrell, S.F.; Snodgrass, S.J. Sensorimotor control in individuals with idiopathic neck pain and healthy individuals: A systematic review and meta-analysis. Archives of physical medicine and rehabilitation 2016. Epub 2016/10/25.
40. Sarig Bahat ,H.; Chen, X.; Reznik, D.; Kodesh, E.; Treleaven, J. Interactive cervical motion kinematics: sensitivity, specificity and clinically significant values for identifying kinematic impairments in patients with chronic neck pain. Manual therapy 2015, 20, 295-302.
41. Tsang, S.M.; Szeto, G..; Lee, R.Y. Movement coordination and differential kinematics of the cervical and thoracic spines in people with chronic neck pain. Clinical biomechanics (Bristol, Avon) 2013, 28, 610-7.
42. de Zoete, R.M.J.; Osmotherly, P.G.; Rivett, D.A.; Snodgrass, S.J. No Differences Between Individuals With Chronic Idiopathic Neck Pain and Asymptomatic Individuals on Seven Cervical Sensorimotor Control Tests: A Cross-Sectional Study. The Journal of orthopaedic and sports physical therapy 2019, 1-37.