Age-related kinematic behavior on fast head-neck rotation target task in non-painful individuals aged from 8 to 85 years old

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Abstract

Kinematic behavior during fast cervical rotations is a useful parameter for assessing sensorimotor control strategies in neck-pain patients. However, in non-painful adults and children, the influence still needs to be explored. We assessed the impact of age on sensorimotor control strategies with computed kinematic variables (total time, mean speed, acceleration, deceleration, overshoots, maximum, minimum speed) during fast rotation task in 80 volunteers stratified in four different age-groups: Children, Young and Old adults and Seniors. Significant effects in Children and Seniors were observed for total time, mean speed, acceleration and deceleration. The test allows to discriminate sensorimotor control strategies between different age groups. Age must therefore be considered as a key parameter when analyzing results

Key words: asymptomatic; sensorimotor; movement; lifetime

1 Introduction

The lifetime prevalence of neck pain is almost 70%, including pre- and adolescent patients, and this increases with age up to the age of 60 (Blanpied et al., 2017; Stahl et al., 2004). Nevertheless, underlying causes of neck pain are poorly understood. Because head rotation is a regular movement performed during everyday activities, this movement represents one of the issues that are of interest in patients with neck pain (Dugailly, Coucke, Salem, & Feipel, 2018). Interestingly, previous studies supported that fast-rotational movements of the head-neck complex may be applied in clinical assessment and/or therapeutic management in patients with idiopathic neck pain (de Zoete, Osmotherly, Rivett, Farrell, & Snodgrass, 2016; Descarreaux, Passmore, & Cantin, 2010; Roijezon et al., 2010; Sarig Bahat, Takasaki, Chen, Bet-Or, & Treleaven, 2015). In view of these reports, fast axial rotation of the neck represents a critical motion to assess.

A target test using the DidRen Laser can be applied in response to real visual targets to standardize a head rotation motor task about 30° (Hage & Ancenay, 2009; Sarig Bahat, Sprecher, Sela, & Treleaven, 2016). Firstly, this test is believed to rely on the integrity of neuro-musculoskeletal structures and of the sensorimotor control system (Treleaven, 2017) i.e. input from the visual, vestibular and proprioceptive systems, particularly the richly innervated cervical spine, which controls head and eye movement and postural stability (Treleaven, 2017). Secondly, the axial head rotation about 30° will preserve the motion from the strain of the passive system (joint capsules, facets, intervertebral disks and ligament) (Panjabi, 1992).

Target-directed head-neck complex movements are fundamental components of individuals' daily activities and usually require high levels of motion speed and accuracy. Speed-accuracy trade-off could be considered as a "signature" of the decision process (Heitz, 2014). This varies according to which motion behavior is emphasized: accuracy or speed (Zhang & Rowe, 2014)] during, for

instance, an aiming task that encompasses amplitude of the movement, the size and position of the target (Descarreaux et al., 2010; Paul M Fitts, 1954; Heitz, 2014; Zhang & Rowe, 2014).

Lack of sensorimotor control of head-neck complex can be explained (Passmore, Burke, & Lyons, 2007; Uthaikhup, Jull, Sungkarat, & Treleaven, 2012) by degeneration of vestibular, visual and neuromuscular functions due to aging or even neck pain in adults and due to immaturity of the central and peripheral nervous and musculoskeletal system in healthy children (Assaiante, 2012; Assaiante, Barlaam, Cignetti, & Vaugoyeau, 2014).

Sensorimotor performance of the head-neck complex can be assessed through various motor tasks requiring complex sensory input and motor output functions (de Zoete et al., 2016). These include the cephalic repositioning test, which estimates the proprioceptive and vestibular systems without interference of the visuomotor system. By using a laser beam placed on the head, the ability of blindfolded participants to actively relocate the head in a neutral position is evaluated after an active rotation movement of the head-neck complex (Revel, Andre-Deshays, & Minguet, 1991). In other settings, the cervical proprioceptive reflex is assessed without focusing on the vestibular system by not including a cervical motor output component of the head-neck complex rotational kinematics. During this test, rotation of the trunk without movement of the head is measured with a 3D Fastrak electronic goniometer, by analyzing the effect of the modified cephalic repositioning test with a “neck torsion test” (Chen & Treleaven, 2013).

For including both sensory and motor component, other tests such as the "virtual reality test" (Sarig Bahat et al., 2016) and "The Fly" (Kristjansson, Hardardottir, Asmundardottir, & Gudmundsson, 2004) use a tracking system placed above the head to respectively measure the accuracy of the ability to follow a virtual target (the fly). Finally, the "DidRen Laser" is a test based on a system developed by our team in the late 2000s. It includes also both sensory and motor component by using a laser beam placed on the head of the participant with the aim to induce fast, low amplitude, and accurate rotational movements of the head-neck complex in response to real

visual targets placed in front of the participant (Hage & Ancenay, 2009). Sensorimotor performance is assessed using the time difference between two successful hits of the targets. This means that, in view of the participant's performance of speed-accuracy trade-off, the shorter the time, the faster and the more accurately the task is accomplished (Heitz, 2014; Liu & Watanabe, 2012; Zhang & Rowe, 2014). In 2009, we showed that the DidRen Laser was a simple and reliable device with a good reproducibility in asymptomatic and symptomatic adult individuals (Hage & Ancenay, 2009). Compared to the other tests, the DidRen Laser is very easy to implement in a clinical setting, but it assesses only temporal variables. This does not allow us to gain insight into sensorimotor strategies adopted by individuals.

Our previous results now need to be extended with a detailed kinematic analysis carried out by a motion capture system. In a recent study by Sarig Bahat et al. (2016), modified kinematics of the head-neck complex were reported in asymptomatic people over 60 compared to young and middle-aged adults (Bahat, Igbariya, Quek, & Treleaven, 2016). This study did not include measurements in children, which we consider essential to provide a better understanding of head-neck complex kinematics and normative data across all stages of the lifespan and to ensure that appropriate age-matched comparisons to participants with neck pain can be made (Hoy, Protani, De, & Buchbinder, 2010).

The aim of this study was to analyze the effect of age from 8 to 85 years old on sensorimotor control strategies adopted by asymptomatic individuals using kinematic variables derived from rotational motion of head-neck complex during the execution of the DidRen Laser test.

2 Material and methods

2.1 Participants

Eighty asymptomatic volunteers (43 females, 37 males) took part in this study and were stratified by age in four groups, children [8-14y]: n=16; young adults [18-35y]: n=29; old adults [36-64y]: n=18; seniors [65-85y]: n=17. They were recruited from colleagues in Saint-Luc University hospital (Brussels, Belgium) and among the researchers' acquaintances. All participants volunteering for the study were informed about the nature of the study. Written consent was obtained from the participants, or from the legal representatives of participating children, before the start of the study. The study was approved by the local ethics committee and conducted in accordance with the declaration of Helsinki.

Participants suffering from any neuromusculoskeletal, neurologic disorder, impaired comprehension, non-correctable visual impairment, deafness, dizziness or any vestibular disorders diagnosed that could influence the performance of head-neck complex rotation, were excluded. Further inclusion criteria were absence of neck pain episodes in the 6 months prior to the study and to ensure that we analyzed asymptomatic participants, a Neck Disability Index (NDI) score of less than or equal to 4% (Kato et al., 2012; Vernon & Mior, 1991). Similarly, all participants were asked to complete a Visual Analogue Scale (VAS) to confirm the absence of pain on the testing day (Ogon, Krismer, Söllner, Kantner-Rumplmair, & Lampe, 1996).

2.2 Instrumentation

The DidRen Laser was used (see (Hage & Ancenay, 2009) for a detailed description of the system and its components). In brief, it is made up of three photosensitive sensors with photocells, a fine laser beam, and a computer equipped with customized software that calculates the time between two consecutive "hits" of the sensors and displays the results. A chair without armrests is

placed at 90 cm from a vertical panel equipped with the 3 sensors; each arranged horizontally and located 52 cm part from each other. The position of the central sensor is just in front of the head of the participant and 2 peripheral sensors induce the participant to perform right and left rotations of maximum 30°.

Three reflective markers were placed on the participant's head (Figure 1), two on the shoulders (acromion), and one on the cervical spine (C7). Three-dimensional recording of the markers positions were carried out at a sampling frequency of 200 Hz during the DidRen Laser test (Hage & Ancenay, 2009), using an optoelectronic system with 8 infra-red cameras (ELITE-BTS, Milan, Italy). A kinematic model composed of 6 anatomical landmarks (Fig. 1) was used. It was adapted from Bulgheroni et al.(1998) and representing the head and trunk segments. The head segment was modeled as a first triangle from the position of the head vertex (Top. H), and left/right side edges (R.H and L.H, respectively) landmarks (at 18 cm either side of the head vertex), and the trunk segment as a second triangle with left/right acromioclavicular joints (L.A and R.A, respectively) and the spinous process of C7 vertebra (Bulgheroni et al., 1998).

2.3 Experimental procedure

All participants received the same instructions about how the experimental procedure was to be conducted and more specifically that of the DidRen Laser test, by watching an explanatory video. The participants wore a helmet to which a laser beam is mounted and sat on a chair. They were instructed to keep their back against the backrest, the palm of hands on the thighs, feet flat on the floor with heels against a stop block placed at the feet of the chair and to refrain from talking during the test.

The procedure of one generated cycle was explained as followed: when the laser beam is pointed correctly at the target (during at least 0.5 s to lower chance), the LED's sensor lights up and

the system emits a sound signal. As soon as the central sensor has been ‘‘hit’’, the participant must, as rapidly as possible, turn his/her head to maximum 30° to the right to hit the right-hand sensor. He/she returns to the central sensor and then rotates the head to maximum 30° to the left to hit the left-hand sensor. The participant completes the cycle by hitting the central sensor for a third time. Then, one cycle is defined systematically with 4 head rotations facing sensors in the same order: 1) from center to the right, 2) from right back to the center, 3) from center to the left and 4) back to the center. A complete trial is composed of 5 cycles. We used non-random generated cycles in order to facilitate intra and inter-subject comparisons.

As in 2009 (Hage & Ancenay, 2009), two DidRen Laser tests were conducted. The first trial was considered as a short warm-up to “familiarize” the participant with the experiment by emphasizing on the adequate sitting position and speed-accuracy execution. So only the second trial was used for data collection and analysis. We didn’t conduct more than two trials to avoid possible fatigue which could lead to a lost precision (Longo & Meulenbroek, 2018).

2.4 Kinematic variables

The DidRen Laser software calculates each time taken by the participant to go from one target’s ‘‘hit’’ (that is when participant stops during at least 0.5 s on the sensor) to another target. Only the total time (TT, in s) to complete the 5 cycles (from the first to the last target) of a trial was included in the data collection.

Head rotational and shoulders-displacement were computed using ELICLINIC software (BTS, Italy) from X, Y, and Z coordinates at each frame. By successive numeric finite difference (n=±5 points), we calculated speed and acceleration of head. The following specific parameters were computed for each kinematics variable: head-rotation range of motion (in °); shoulders displacement (in °), overshoot (OS, in °) was computed as the difference between peak rotation

amplitude and stabilized mean rotation amplitude; maximum/minimum rotational speed (MaxS, MinS, in ° s^{-1}); average rotational speed (MeanS, in ° s^{-1}); average rotational acceleration/deceleration (Acc, Dec, in ° s^{-2}). All variables were calculated during 5 consecutive cycles and averaged.

2.5 Statistical analysis

To assess the effect of age on the average variables, a one-way ANOVA with *post hoc* Holm-Sidak method for pairwise multiple comparisons was carried out when normally distributed and with *post hoc* Dunn's method for pairwise multiple comparisons if normality test failed. All statistical procedures were performed with SPSS version 25 and SigmaPlot 13 with a significant level at 5%.

3 Results

Total sample size consisted of 87 participants from which 7 participants were excluded due to an NDI score >4%. The anthropometric characteristics of the participants are listed in Table 1. Range of head-rotations did not exceed 30° (25.8±0.28°) and shoulders-displacements were negligible (0.27±1.19°).

All results are showed in Figure 2. A significant effect ($p<0.05$) of age was observed for 4 kinematic variables in Children and Seniors. Total Time (s) was longer in Children (68.898 [60.624-87.342]) compared to Young Adults (49.562 [45.587-55.585]) and Old Adults (51.679 [48.402-55.831]). It was also longer in Seniors (56.999 [52.305-67.617]) compared to Young Adults (49.562 [45.587-55.585]). Mean Speed (° s^{-1}) was lower in Children (9.375±2.347) and Seniors (10.595±2.406) compared to Young Adults (13.724±1.899) and Old Adults (13.332±2.389). Acceleration (° s^{-2}) was lower for Children (8.4 [7.6-10.2]) compared to Young Adults (11.1 [8.8-15.3]) and Old Adults (12.0 [8.4-15.3]). Deceleration (° s^{-2}) was lower for Children (-1.9 [-2.6- -1.4]) compared to Young Adults (- 2.9 [-3.7- -2.4]) and Old Adults (- 3.2 [-3.7- -2.3]).

4 Discussion

The results of the study reveal significant effects in asymptomatic Children and Seniors groups for four rotational kinematic variables: total time, mean speed, acceleration and deceleration. These kinematic differences were observed during the DidRen Laser test, showing its capacity to discriminate age-related differences.

Velocity and the derivate forms were chosen to analyze the performance of age-group participants in accordance with previous studies (Roijezon et al., 2010; Sarig Bahat et al., 2016). Sarig Bahat et al. (2016) showed that the most powerful age-groups differences were Velocity Peaks and Number of Velocity Peaks (Bahat et al., 2016). With a different task and method of calculation, our kinematic variables such as Total Time, Mean Speed, Acceleration and Deceleration appeared to be very significant especially with the groups of Children and Seniors.

To reach the speed-accuracy required by our protocol: “turn your head faster as you can”, participants needed to trade-off with their sensorimotor ability to perform the rotational movement. In 1954, Fitt described the speed-accuracy trade-off that exists when people, including seniors and children (Passmore et al., 2007; Smits-Engelsman, Sugden, & Duysens, 2006), are involved in accuracy constrained target-aiming task. The theory was that movement time would increase linearly as the size of the targets decreases or the distance between the targets increases (Paul M Fitts, 1954; Passmore et al., 2007).

In accordance with Fitts’ law, we showed that Seniors and Children needed to be slower (Total Time, Mean Speed, Acceleration, Deceleration) (Descarreaux et al., 2010; Paul M Fitts, 1954; P. M. Fitts, 1992; Smits-Engelsman et al., 2006) to become as precise as Young and Old people (no significant differences for Overshoot in all age-groups). Our results have demonstrated the ability for Children and Seniors to adapt their speed to be at least as accurate as Young and Old Adults. Similarly, we have also demonstrated that both Adults groups have adapted their speed.

Indeed, both Adults groups showed an average of speed 10 times less than the average of speed (Vmean) obtained by Sarig Bahat's participants of the same ages (Bahat et al., 2016). Actualy, even if Sarig Bahat's participants were asked to move their head fast, they could take longer time (seven seconds) to point the target after having produced the motion. So, they didn't need to trade-off with their speed and accuracy as much as needed to accomplish the DidRen Laser test.

Even if the kinematic variables assessed in this study do not allow us to differentiate the subsystem(s) of the sensorimotor control, it is plausible that senior-related modifications can be due to dysfunction in neck proprioception, vestibular and visual systems (Passmore et al., 2007; Uthaikhup et al., 2012). Slower Children-related performances could be due to slow maturation of the sensorimotor system (Assaiante, 2012; Assaiante, Mallau, Viel, Jover, & Schmitz, 2005) and immaturity in the development of the central nervous system (Assaiante, 2012; Assaiante et al., 2005; Corporaal et al., 2017; Tau & Peterson, 2010).

The results of the present study should be seen in the light of several methodological clarifications. Firstly, standardization of instructions and better understanding of participants, especially for children and some older participants, were increased by using a tablet computer with an explanatory video of the DidRen Laser test. Secondly, to avoid measurement errors that could increase variability of our results, we standardized the posture of the head, trunk, limbs and the height of visual reference and the influence of the scapular girdle displacement while performing head-neck complex rotations (Gueguen, Vuillerme, & Isableu, 2012; Scotto Di Cesare et al., 2013; Scotto Di Cesare, Macaluso, Mestre, & Bringoux, 2015). Thirdly, to avoid influencing stability of the neck and for being more functional, we didn't secure the shoulder with a seat-belt (Cromwell, Aadland-Monahan, Nelson, Stern-Sylvestre, & Seder, 2001). Fortunately, our results concerning the scapular girdle rotation displacement showed that it was marginal for all participants and confirmed

that they respected the instruction not to move their shoulders during the test. Thanks to this option, the DidRen Laser test could be used more easily for future clinical study.

This study presents some limitations. First, neck ROM was limited to 30°, while this allowed us to avoid the strain of the neck passive system and to improve input from the neck, it corresponds to about 30 % of the total cervical amplitude and may not be perceived as clinically relevant. Second, only head-neck rotational movement was assessed. As rotation seems to be a regular movement during daily activities, the assessment of other motion directions (e.g. flexion/extension) appeared to have limited interest. Third, we used for the test regular generating head rotation cycles. Indeed, use randomly generated cycles might reduce an induced anticipatory motions and predictions of participants but that has not yet been investigated for this kind of test.

In conclusion, a difference was observed in sensorimotor control behavior in both children and senior individuals compared to adults. The DidRen test proves to be discriminant to sensorimotor control strategies linked to age. When using this test, age must be considered as a key parameter when analyzing results of patients versus non-painful individuals.

Declaration of interest

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References

Assaiante, C. (2012). Action and representation of action during childhood and adolescence: a functional approach. *Neurophysiol Clin, 42*(1-2), 43-51. doi:10.1016/j.neucli.2011.09.002

Assaiante, C., Barlaam, F., Cignetti, F., & Vaugoyeau, M. (2014). Body schema building during childhood and adolescence: a neurosensory approach. *Neurophysiol Clin, 44*(1), 3-12. doi:10.1016/j.neucli.2013.10.125

Assaiante, C., Mallau, S., Viel, S., Jover, M., & Schmitz, C. (2005). Development of postural control in healthy children: a functional approach. *Neural Plast, 12*(2-3), 109-118; discussion 263-172. doi:10.1155/np.2005.109

Bahat, H. S., Igbariya, M., Quek, J., & Treleaven, J. (2016). Cervical Kinematics of Fast Neck Motion across Age. *Journal of Novel Physiotherapies, 6*(5). doi:10.4172/2165-7025.1000306

Blanpied, P. R., Gross, A. R., Elliott, J. M., Devaney, L. L., Clewley, D., Walton, D. M., . . . Robertson, E. K. (2017). Neck Pain: Revision 2017. *J Orthop Sports Phys Ther, 47*(7), A1-a83. doi:10.2519/jospt.2017.0302

Bulgheroni, M. V., Antonaci, F., Ghirmai, S., Sandrini, G., Nappi, G., & Pedotti, A. (1998). A 3D kinematic method for evaluating voluntary movements of the cervical spine in humans. *Funct Neurol, 13*(3), 239-245.

Chen, X., & Treleaven, J. (2013). The effect of neck torsion on joint position error in subjects with chronic neck pain. *Man Ther, 18*(6), 562-567. doi:10.1016/j.math.2013.05.015

Corporaal, S. H. A., Gooijers, J., Chalavi, S., Cheval, B., Swinnen, S. P., & Boisgontier, M. P. (2017). Neural predictors of motor control and impact of visuo-proprioceptive information in youth. *Hum Brain Mapp*. doi:10.1002/hbm.23754

Cromwell, R. L., Aadland-Monahan, T. K., Nelson, A. T., Stern-Sylvestre, S. M., & Seder, B. (2001). Sagittal plane analysis of head, neck, and trunk kinematics and electromyographic activity during locomotion. *J Orthop Sports Phys Ther, 31*(5), 255-262. doi:10.2519/jospt.2001.31.5.255

de Zoete, R. M., Osmotherly, P. G., Rivett, D. A., Farrell, S. F., & Snodgrass, S. J. (2016). Sensorimotor control in individuals with idiopathic neck pain and healthy individuals: A systematic review and meta-analysis. *Arch Phys Med Rehabil*. doi:10.1016/j.apmr.2016.09.121

Descarreaux, M., Passmore, S. R., & Cantin, V. (2010). Head movement kinematics during rapid aiming task performance in healthy and neck-pain participants: the importance of optimal task difficulty. *Man Ther, 15*(5), 445-450. doi:10.1016/j.math.2010.02.009

Dugailly, P. M., Coucke, A., Salem, W., & Feipel, V. (2018). Assessment of cervical stiffness in axial rotation among chronic neck pain patients: A trial in the framework of a non-manipulative osteopathic management. *Clin Biomech (Bristol, Avon), 53*, 65-71. doi:10.1016/j.clinbiomech.2018.02.005

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology, 47*(6), 381.

Fitts, P. M. (1992). The information capacity of the human motor system in controlling the amplitude of movement. 1954. *J Exp Psychol Gen, 121*(3), 262-269.

Gueguen, M., Vuillerme, N., & Isableu, B. (2012). Does the integration of haptic and visual cues reduce the effect of a biased visual reference frame on the subjective head orientation? *PLoS One, 7*(4), e34380. doi:10.1371/journal.pone.0034380

Hage, R., & Ancenay, E. (2009). Identification of a relationship between cervical spine function and rotational movement control. *Ann Phys Rehabil Med, 52*(9), 653-667. doi:10.1016/j.rehab.2009.04.003

Heitz, R. P. (2014). The speed-accuracy tradeoff: history, physiology, methodology, and behavior. *Front Neurosci, 8*, 150. doi:10.3389/fnins.2014.00150

Hoy, D. G., Protani, M., De, R., & Buchbinder, R. (2010). The epidemiology of neck pain. *Best Pract Res Clin Rheumatol, 24*(6), 783-792. doi:10.1016/j.berh.2011.01.019

Kato, S., Takeshita, K., Matsudaira, K., Tonosu, J., Hara, N., & Chikuda, H. (2012). Normative score and cut-off value of the Neck Disability Index. *J Orthop Sci, 17*(6), 687-693. doi:10.1007/s00776-012-0276-y

Kristjansson, E., Hardardottir, L., Asmundardottir, M., & Gudmundsson, K. (2004). A new clinical test for cervicocephalic kinesthetic sensibility: "the fly". *Arch Phys Med Rehabil, 85*(3), 490-495.

Liu, C. C., & Watanabe, T. (2012). Accounting for speed-accuracy tradeoff in perceptual learning. *Vision Res, 61*, 107-114. doi:10.1016/j.visres.2011.09.007

Longo, A., & Meulenbroek, R. (2018). Precision-Dependent Changes in Motor Variability During Sustained Bimanual Reaching. *Motor Control, 22*(1), 28-44. doi:10.1123/mc.2016-0013

Ogon, M., Krismer, M., Söllner, W., Kantner-Rumplmair, W., & Lampe, A. (1996). Chronic low back pain measurement with visual analogue scales in different settings. *Pain, 64*(3), 425-428.

Panjabi, M. M. (1992). The stabilizing system of the spine. Part I. Function, dysfunction, adaptation, and enhancement. *J Spinal Disord, 5*(4), 383-389; discussion 397.

Passmore, S. R., Burke, J., & Lyons, J. (2007). Older adults demonstrate reduced performance in a Fitts' task involving cervical spine movement. *Adapt Phys Activ Q, 24*(4), 352-363.

Revel, M., Andre-Deshays, C., & Minguet, M. (1991). Cervicocephalic kinesthetic sensibility in patients with cervical pain. *Arch Phys Med Rehabil, 72*(5), 288-291.

Roijezon, U., Djupsjobacka, M., Bjorklund, M., Hager-Ross, C., Grip, H., & Liebermann, D. G. (2010). Kinematics of fast cervical rotations in persons with chronic neck pain: a cross-sectional and reliability study. *BMC Musculoskelet Disord, 11*, 222. doi:10.1186/1471-2474-11-222

Sarig Bahat, H., Sprecher, E., Sela, I., & Treleaven, J. (2016). Neck motion kinematics: an inter-tester reliability study using an interactive neck VR assessment in asymptomatic individuals. *Eur Spine J*. doi:10.1007/s00586-016-4388-5

Sarig Bahat, H., Takasaki, H., Chen, X., Bet-Or, Y., & Treleaven, J. (2015). Cervical kinematic training with and without interactive VR training for chronic neck pain - a randomized clinical trial. *Man Ther, 20*(1), 68-78. doi:10.1016/j.math.2014.06.008

Scotto Di Cesare, C., Anastasopoulos, D., Bringoux, L., Lee, P. Y., Naushahi, M. J., & Bronstein, A. M. (2013). Influence of postural constraints on eye and head latency during voluntary rotations. *Vision Res, 78*, 1-5. doi:10.1016/j.visres.2012.11.011

Scotto Di Cesare, C., Macaluso, T., Mestre, D. R., & Bringoux, L. (2015). Slow changing postural cues cancel visual field dependence on self-tilt detection. *Gait Posture, 41*(1), 198-202. doi:10.1016/j.gaitpost.2014.09.027

Smits-Engelsman, B. C., Sugden, D., & Duysens, J. (2006). Developmental trends in speed accuracy trade-off in 6-10-year-old children performing rapid reciprocal and discrete aiming movements. *Hum Mov Sci, 25*(1), 37-49. doi:10.1016/j.humov.2005.12.002

Stahl, M., Mikkelsson, M., Kautiainen, H., Hakkinen, A., Ylinen, J., & Salminen, J. J. (2004). Neck pain in adolescence. A 4-year follow-up of pain-free preadolescents. *Pain, 110*(1-2), 427-431. doi:10.1016/j.pain.2004.04.025

Tau, G. Z., & Peterson, B. S. (2010). Normal development of brain circuits. *Neuropsychopharmacology, 35*(1), 147-168. doi:10.1038/npp.2009.115

Treleaven, J. (2017). Dizziness, Unsteadiness, Visual Disturbances, and Sensorimotor Control in Traumatic Neck Pain. *J Orthop Sports Phys Ther*, 1-25. doi:10.2519/jospt.2017.7052

Uthaikhup, S., Jull, G., Sungkarat, S., & Treleaven, J. (2012). The influence of neck pain on sensorimotor function in the elderly. *Arch Gerontol Geriatr, 55*(3), 667-672. doi:10.1016/j.archger.2012.01.013

Vernon, H., & Mior, S. (1991). The Neck Disability Index: a study of reliability and validity. *J Manipulative Physiol Ther, 14*(7), 409-415.

Zhang, J., & Rowe, J. B. (2014). Dissociable mechanisms of speed-accuracy tradeoff during visual perceptual learning are revealed by a hierarchical drift-diffusion model. *Front Neurosci, 8*, 69. doi:10.3389/fnins.2014.00069

Table 1: Anthropometric characteristics of the participants

Subjects	Global (n=80)	Ch (n=16)	YA (n=29)	OA (n=18)	S (n=17)
Age (years), mean±SD	40.25±28	11±2	24±3	53±7	73±5
Sex *(men/women)*, n	43/37	5/11	13/16	10/8	9/8
BMI ($kg\ m^{-2}$), mean±SD	22.19± 4.4	17.31±1.99	22.9±2.99	24.33±4.24	24.48±3.25
NDI (50), median [Q1-Q3]	2 [1-4]	0 [0-2]	2 [1-2.25]	2 [1-4]	2 [0-4]
VAS (0-10), median [Q1-Q3]	0 [0-0]	0 [0-0]	0 [0-0]	0 [0-0.1]	0 [0-0.5]

Global= all age-groups, Ch= Children, YA= Young Adults, OA= Old Adults, S= Old Adults, S= Seniors, SD= Standard Deviation, BMI = Body Mass Index, Q1 = First Quartile, Q3 = Third Quartile, NDI=Neck Disability Index

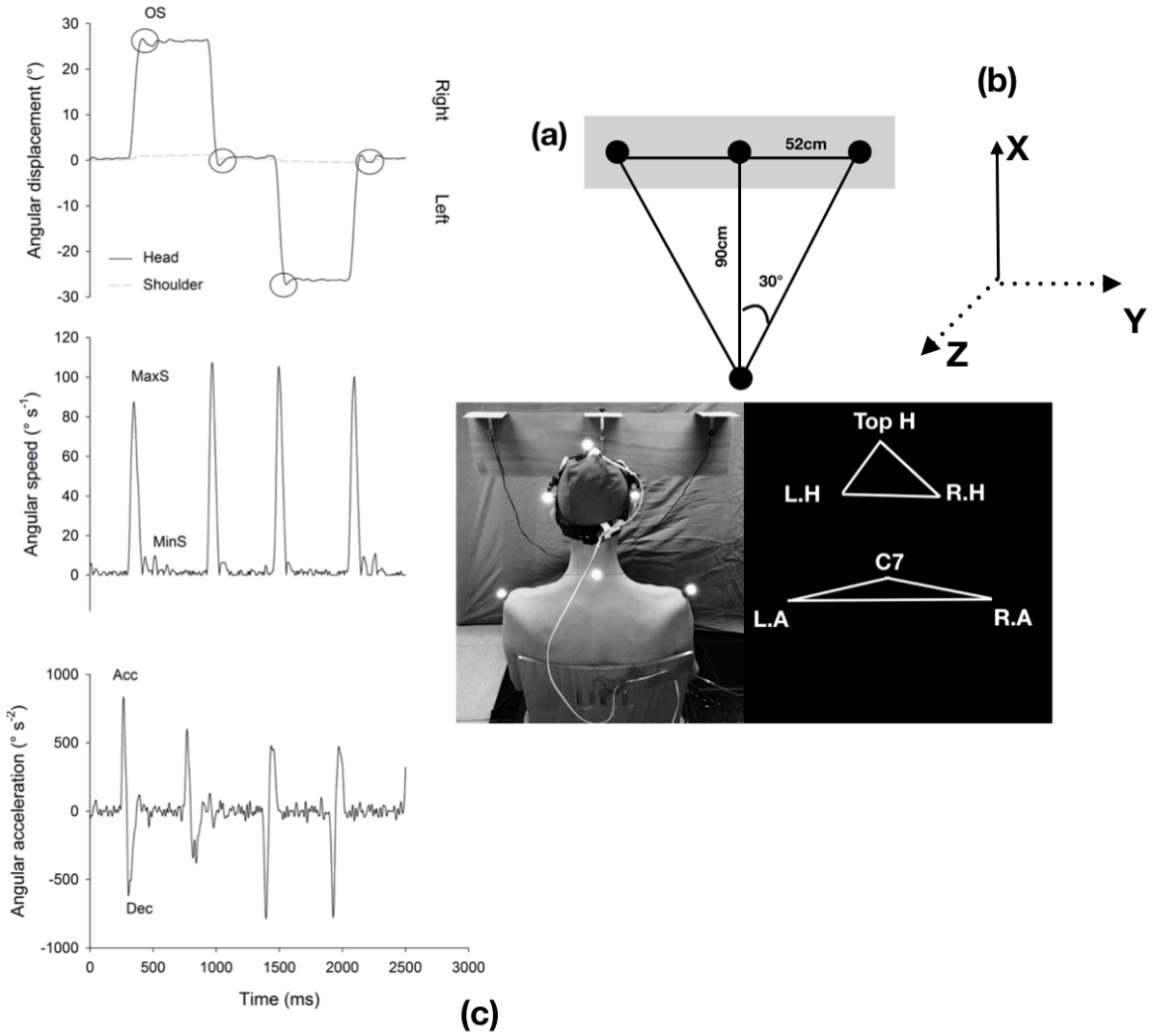

Fig. 1. (a). DidRen Laser installation device including the 3 photosensitive sensors and the placement of markers on the head and the shoulders. (b) Head rotation is executed around a vertical axis (X) in a horizontal plane (Y-Z). (c) Example of one rotational kinematic cycle with Angular displacement (showing OS on the circles), Angular speed (showing MaxS and MinS in absolute value) and Angular acceleration (showing Acc and Dec).

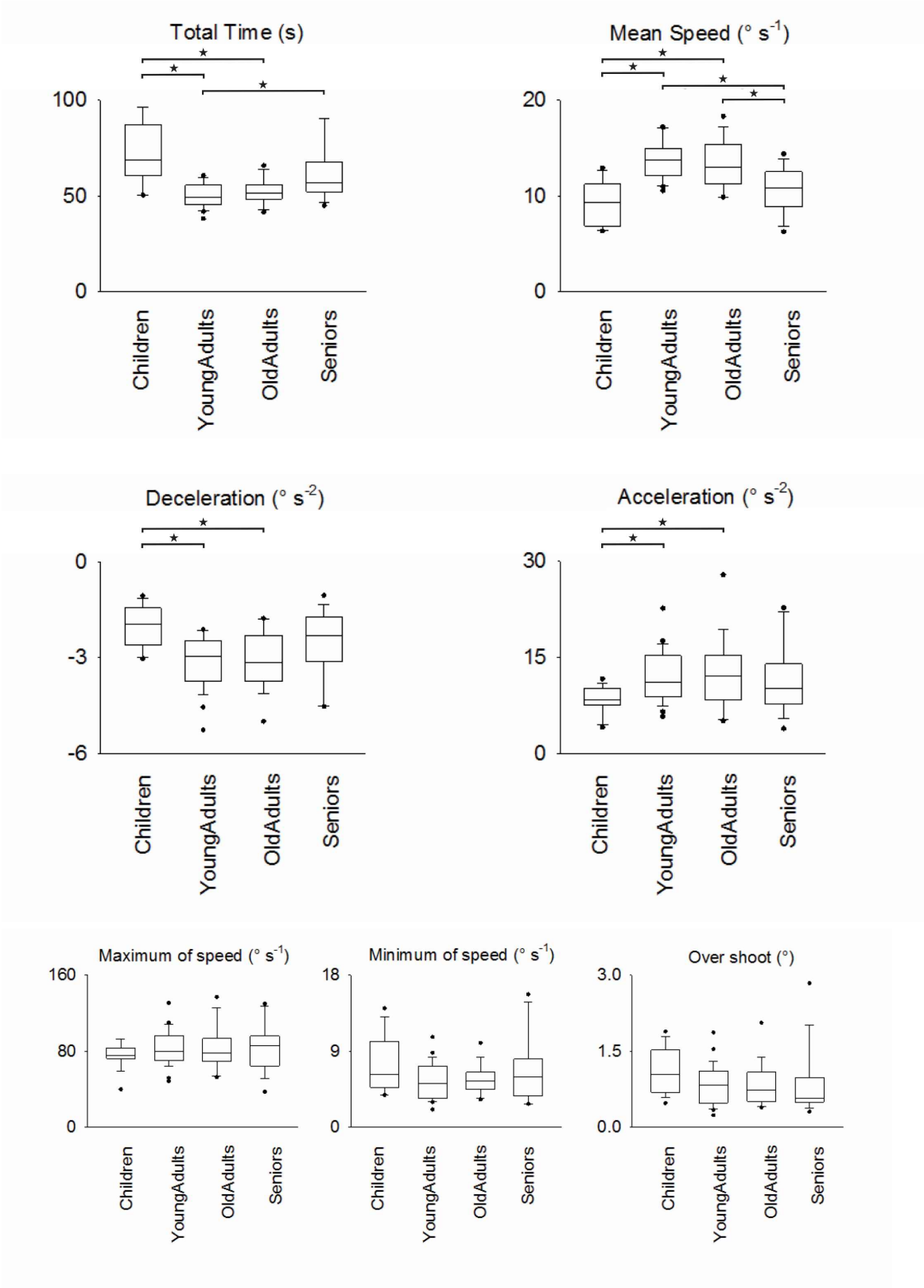

Fig. 2. Box-plots (interquartile range) for all age effect measurements. First four box-plots are for age-groups significant kinematic variables with *post hoc* comparisons: ★ *P<0.05*. The three horizontal box-plots are for non-significant kinematic variables.