Cervical Motion Testing: Methodology and Clinical Implications

Tamara Prushansky, PhD, and Zeevi Dvir, PhD

Abstract

Background: Measurement of cervical motion (CM) is probably the most commonly applied functional outcome measure in assessing the status of patients with cervical pathology. In general terms, CM refers to motion of the head relative to the trunk as well as conjunct motions within the cervical spine.

Special Features: Multiple techniques and instruments have been used for assessing CM. These were associated with a wide variety of parameters relating to accuracy, reproducibility, and validity. Modern measurement systems enable recording, processing, and documentation of CM with a high degree of precision.

Summary: Cervical motion measures provide substantial information regarding the severity of motion limitation and level of effort in cervically involved patients. They may also be used for following up performance during and after conservative or invasive interventions. (J Manipulative Physiol Ther 2008;31:503-508)

Key Indexing Terms: *Neck; Range of Motion, Articular; Neck Pain; Outcome Assessment (Health Care); Spine; Cervical Vertebrae*

Terminology

Historically, the term cervical motion (CM) has been interchangeably used for describing the motion of both the head relative to a ‘stationary’ reference system and cervical vertebrae in relation to each other including the C0-C1 segment, which effectively relates to the motion of the head relative to C1.

With the advent of sophisticated noninvasive external measurement instruments for capturing 3-dimensional motion as well as radiological imaging systems, the study of CM has significantly progressed. However, the radiological branch of CM is largely invasive (radiation-wise) and is rarely used for purposes other than diagnosis of cervical pathology or follow-up after interventions. Moreover, although radiological findings of CM serve as the gold standard for head motion, for measuring vertebral conjunct (coupled) motions, and for describing instantaneous axes of motion, the context within which conservative treatment and rehabilitation operate relate only to *head* motion hitherto referred as CM. The latter is the subject matter of this article.

Cervical motion is a more comprehensive concept than what is commonly perceived because it includes not only the angular excursions of the head relative to the 3 major anatomical planes but also the first (velocity) and second (acceleration) derivatives of head displacement. Moreover, conjunct or coupled motions have attracted growing interest among clinicians. However, the scientific investigation of head velocity and acceleration has not received the extent of attention compared to, for example, the lumber spine. This may be due to adverse effects that may occur while trying to move the head faster than what is comfortable and safe for the patient. Therefore, the issue of CM indeed refers to the angular range of motion (RoM), which is commonly subdivided into the 6 primary motions as follows: flexion, extension, right lateral flexion (RLF) and left lateral flexion, and right rotation (RR) and left rotation. Furthermore, the term CM invariably refers to active rather than passive motion.

Methods

A PubMed literature search based on the keywords cervical/head/neck RoM was conducted. The search yielded 130 articles that were reviewed according to the criteria and issues discussed below.

Results

Clinical Relevance of CM

There are 4 clusters of distinct cervical pathologies where CM variations are of significance: (I) traumatic conditions involving bony-ligamentous support systems of the cervical

Department of Physical Therapy, Sackler Faculty of Medicine, Tel Aviv University, Tel Aviv, Israel.

Submit requests for reprints to: Tamara Prushansky, PhD, Department of Physical Therapy, Sackler Faculty of Medicine, Tel Aviv University, Tel-Aviv 69978, Israel
(e-mail: *prushans@post.tau.ac.il*).

Paper submitted March 24, 2008; in revised form May 13, 2008.
0161-4754/$34.00

doi:10.1016/j.jmpt.2008.08.004

spine, which (a) potentially compromise the spinal cord and/or stability of the spine (these conditions may be assessed only after stability of the cervical spine has been achieved) and (b) do not jeopardize the spinal cord involving mostly soft tissues, for example, whiplash; (II) degenerative and rheumatic diseases of the cervical spine, for example, spinal stenosis, ankylosis spondylitis; (III) neurological and congenital conditions such as cerebrovascular accident, headache, torticollis, cervical dystonia, and cerebral palsy; and (IV) acquired pain-related limitations of CM, for example, postural, work related, stress related. The assessment and treatment of all of the above-mentioned conditions will require measurement of CM.

Measurement of CM

The most basic method of CM assessment is the *visual*. Although widely utilized in the clinic, the use of visual estimation (VE) has been strongly challenged. In a leading article, the comparative reproducibility of VE, universal goniometry, and the cervical RoM (CROM) device has been studied.[1] It has been indicated that VE was distinguished by poor reproducibility (intraclass correlation coefficient, 0.42-0.7 except for 0.82 in RR) and hence could not possibly serve as an efficient outcome measure.

Linear estimates of CM refer correspondingly to the 3 principal planes: the distance between the midline of the chin to the sternal notch serve for estimating flexion and extension, between the midline of the chin and the acromion process for rotation, and from the lower tip of the earlobe to the acromion process for lateral flexion.[2,3] It was concluded that this form of estimation of CM had a major drawback due to the large variety of human size.

In terms of *angular* measurements, the most common instrument for measuring CM is probably the 2-arm goniometer, which is in wide use for assessing motion in other joints. Being small, portable, of reasonable precision, and cheap while considering the relatively large angular excursions of the head, the goniometer would have been a very effective instrument for this particular purpose. However, there are 2 major problems: one relates to the alignment of the goniometer's axis with the 'axis' of the particular head motion and the other concerns placement or positioning of the arms relative to the head and the reference frame (torso). Specifically, head motion in the frontal and sagittal planes results from small intervertebral angular displacements that, on their own, represent multiaxial motions. Thus, a significant error is introduced in assuming a single axis. On the other hand, although head motion in the transverse plane is substantially around the dens, the structure of the goniometer, as well as its alignment with the top of the skull relative to the C1-C2 joint, introduces another source of error.[1,4] Significantly, for all 3 planes, the stationary arm is held by the tester, itself a source of error. Therefore, the derivation of valid data from simple goniometric measurements of the head is problematic, at best.

Another type of goniometric measurements is referred to as the gravity or pendulum goniometer.[5,6] As the name implies, this goniometer has a moving arm that is immersed in fluid. Attached to a moving segment, substantially in a plane perpendicular to the horizontal, the angular excursion of the arm corresponds to the RoM of the segment, providing the more proximal segment is fixed. Using this instrument with head adapter,[5] the CM was measured in the sagittal and frontal planes while sitting and in the transverse plane in the supine position. Measuring with this instrument was distinguished by high interrater reliability compared to the universal goniometer. It should be mentioned that reproducibility was assessed based on ICC in a very small sample, and therefore, the absolute error of measurement and, significantly, an intrarater analysis were not available.

The next development in mechanical goniometry was in the form the CROM device, consisting of 2 pendulum goniometers for measuring CM in sagittal and frontal planes and a single magnetic ('compass') goniometer used for measuring rotation in the seated position. All 3 goniometers are housed within a plastic frame that is mounted in 2 pieces on the head. Measuring head rotation in the seated position offers a clear advantage over the simple goniometer, which may be used only in the supine position. Reproducibility of findings derived from the CROM device is clinically satisfactory.[4] The CROM-based findings relating to the sagittal plane were also very highly correlated with radiographic measurements supporting the validity of this instrument.[7] Electronic digital inclinometer EDI-320 was found to be valid in normal population[8] and reproducible in patients with neck pain.[9]

Recently, a new handheld device has been added to the arsenal of CM-measuring instruments—the digital inclinometer (DI). The DI is an electronic spirit that displays its absolute angular inclination, at a resolution of 0.1°, using a small screen. The instrument is placed on the moving segment, and the values are normally read off at the segment's initial and final positions. The difference in values is the segment RoM. Recording of CM in sitting and along the sagittal and frontal planes is distinguished by relatively coupled-free motion between the head and the thorax. Indeed, a recent unpublished study indicated a good compatibility between the DI and the Zebris CMS 70P instrumented system. On the other hand, measurement of rotation using the DI requires that the subject assumes a supine lying position. In this case, the DI-associated scores were significantly greater than those obtained in the seated position (using the Zebris).

State of the art equipment used for CM assessment can capture in real-time the 3-dimensional kinematics of the head using dedicated measurement systems or general purpose systems. Dedicated systems operate on the principle that the reference system is attached to the ribcage or spinal column, whereas the mobile coordinate system is attached to the head. Different designs are in use comprising electrically monitored mechanical linkages (CA 6000),[10-13] electromagnetic sensors (Flock of Birds),[14,15] optoelectronic instrument (Elite system),[16] and ultrasound-based sensors (Zebris).[17] These systems have upgraded the recording, analysis, and interpretation of the motion data by offering high accuracy (up to 0.01°), reduction of the examiner-bound error of measurement, recording of coupled motions, calculation of higher-order displacement derivatives, and automatic documentation. The major drawback of the dedicated systems is their cost, which limits their employment.

Test Protocol and Documentation

Although no standard protocol for measuring CM has been formally recognized, the commonly used protocol is based on sequentially recording movements in the sagittal, then transverse and coronal planes. The Guides to the Evaluation of Permanent Impairment also stipulate that within-plane movements should be conducted in such a manner that the 2 primary motions comprising a plane should be measured alternately. The Guides recommend 3 repetitions of each measurement. The question whether the order of measurement is of significance has been examined using 4 different protocols[18]: A—reciprocal with a pause between consecutive motions within the same plane, B—same as protocol A but without a pause, C—3 repetitions of the same primary direction, and D—random order of primary directions but still with 3 repetitions. Using the Zebris system and a test-retest intrarater design, it was revealed that protocol D was associated with the poorest reproducibility, whereas protocol A, B, or C was acceptably consistent.

Documentation of CM may be rendered either in the form of full range, for example, a total value for the sagittal, frontal, or transverse planes resulting in 3 measures or reporting the primary directions such as flexion and extension, resulting in 6 scores.[19] In addition, unless explicitly mentioned, CM refers to active movement of the head.

Psychometric Properties

Interpretation of reported findings in the literature is very difficult due to 2 major sources. The first is the diversity of measurement tools or instruments, and the second is nonuniformity in analyzing the results, specifically with respect to reproducibility and validity of the test findings.[19]

Normative values derived from specific instruments, protocols, and sufficiently large populations do not actually exist. Interestingly, the Guides quote a set of CM values in apparently healthy adults relating to each of the 6 primary directions as follows: flexion −60, extension −75, RR and LR −89, left lateral flexion and RLF −45. If these scores are to be interpreted as mean values, the lack SD or SE is most conspicuous preventing, for example, medicolegal assessment of CM limitations. Moreover, there is no division into sex or age group, rendering the system as a guiding tool. On the other hand, pooling of a relatively large number of studies and using a meta-analysis pointed out to the following angular ranges of motion: flexion, 43° to 73°; extension, 33° to 77°; rotation, 60° to 86°, and lateral flexion, 41° to 54°. The mean values were the following: flexion, 52°; extension, 71°; rotation, 72°; and lateral flexion, 43°.[19] Most of the references refer to sex differences where women posses larger CM in comparison to men. However, these differences are small: 2° to 4° and generally not statistically significant.[19] Age has an adverse effect on CM, namely, there is a reduction, at a rate of 4° per decade, which is uniform in men and women.[4] Largely similar results were previously obtained[20] using a Zebris system, namely, extension was reduced 5.9° per decade, whereas 3° to 4° per decade were noted for rotation and lateral flexion.

Coupled movements are a natural part of CM together with primary movements and follow specific patterns in symptom-free subjects but are distinguished by individual variations.[20] Significantly, large variations were recorded in different studies amounting to 5% to 75% of the range in the primary motion.[12,13] Coupling usually refers to rotation in lateral bending and vice versa where the direction is to the same side, that is, RLF is associated with RR. Moreover, it has been suggested that there was more conjunct rotation in lateral flexion than vice versa. Whether age has an effect of coupling is controversial. Based on a group of apparently healthy women (n = 60) and men (n = 60), Trott et al[14] reported that age had only a minor effect, whereas Malmstrom et al,[20] based on a similar sample (size and subjects), suggested that age did have a significant effect.

In recent years, another measure that relates to the additive value of the 6 CROMs (total CROM [TCROM]) has been introduced. In apparently healthy individuals, women and men aged 21 to 55, the TCROM amounted to 353° ± 46°.[21] The advantage of using the TCROM is in its ability to depict, in a compact manner, the general mobility of the cervical spine. Moreover, as far as patients with whiplash are concerned, it was indicated that the reductions in the primary directions were uniform and proportional, and therefore, the TCROM could also serve as an independent outcome measure.[21]

Validity

Validation should be perceived in terms of both comparison to the gold standard (radiological measurements) and agreement among different systems. The general picture emerging from the studies is a fairly good intersystem agreement as well as compatibility between the invasive and noninvasive techniques. It should be emphasized that measurement of CM poses a relatively simple challenge because the head is a well-defined segment that allows substantially direct contact between the skull and the sensor.

Thus, CM findings may be considered generally valid. However, of major importance is the topic of reproducibility.

Reproducibility

Reproducibility refers to the extent of difference (or stability) between repeated measurements of a given parameter. The modern interpretation of the main objective of reproducibility studies is the determination of cutoff values based on which a clinically relevant change or the so-called smallest real difference (SRD) would be determined.[22] It should be noted that the 'repetitions' should be conducted over a clinically relevant period, that is, days or weeks. If the repetitions are performed within the same test session, the term repeatability is more appropriate, and in this case, the commonly used parameter is the coefficient of variation (CV). The CV is the ratio obtained by dividing the SD of the repetitions by their mean value; by multiplying by 100, the CV relates in percentage to the consistency of performance. The typical CV of CM in healthy subjects is within 5%, which, compared to other performance-based variables (eg, strength), indicates a very consistent performance.[23]

Differences between measurements may be derived from 4 major error sources: the subject (patient), the measurement instrument, the examiner, and the measurement protocol. Statistical analysis of the reproducibility is often directed at highlighting the error source. Traditionally, reproducibility was analyzed using correlational parameters such as Pearson r (r_p) and ICCs. However, these relative parameters are sensitive to the range of individual scores, that is, the wider the range the higher the r_p or ICC. Thus, heterogeneous samples tend to produce higher correlations. In addition and even more significantly, neither of these can provide any clinical insight regarding the actual difference (in the case of CM, in degrees) between the test conditions. In addition, 2 sets of measurements may be perfectly correlated although representing a significant difference between them. Therefore, in recent years, there has been a retreat from correlational techniques and emergence of absolute parameters such as the standard error of measurement (SEM), which quantifies the error, in numerical form and in the unit of measurement. Based on the SEM, the SRD can be derived.

Most studies have not calculated the SEM, whereas correlation coefficients varied according to the device. Both the VE and goniometric measurements yielded ICCs of around 0.8 for intratester but very poor intertester ICCs.[1] The respective ICCs for the CROM device were 0.73 to 0.95. Other correlations were quoted for the CA 6000 (R^2 = 0.76),[12] ISOTRACK (r_p = 0.7-1.0),[14] and CA 6000 (R^2 = 0.43-0.73).[10] Two independent studies related to the Zebris system. In an earlier study, r_p ranged from 0.78 to 0.88, whereas the SEMs were between 3.5° (lateral flexion) and 7.66° (flexion).[17] In a latter study, ICCs of 0.80-0.94 for full cycle and SEMs of between 4.25° and 7.88° were reported, in almost perfect agreement with the earlier study.[24]

Gravity inclinometer-based intertester reproducibility of CM (with 5 minutes time interval) in patients with mechanical neck pain yielded SEMs of 3.6° in lateral flexion to 6.8° in flexion, similar to those obtained in healthy subjects.[25] In another study, using digital inclinometry in patients with neck pain, the intratester (time interval, 10 minutes) SRDs for a full cycle were 11.1°, 13.5°, and 10.4° in the sagittal, transverse, and frontal plane, respectively. The intertester (time interval, 5 minutes) SRDs were 17.0°, 17.0°, and 24.6° for the sagittal, frontal, and transverse planes, respectively.[9] Collectively, these findings point out to a relatively stable trait, which enable clinical inference from CM measurements.

Use of CM as an Outcome Measure

As mentioned earlier in this article, measurement of CM is very commonly applied in assessing the functional status of patients with neck involvement. Of note, the functional model used by the AMA's Guides to the evaluation of permanent impairment relies to a great extent on the measurement of CM and the assignment of percent impairment based on subdivisions of the so-called normative angular values in each of the 6 primary directions.[26] In this section, we describe the use of CM as an outcome measure in a number of pathologies.

Measuring CM using 3-dimensiona–dedicated systems has been performed in our laboratory on a group of patients with chronic whiplash who were candidates for cervical radiofrequency neurotomy.[27] There were 2 major objectives: first, to find out whether patients had specific CM profile and as a derived aim to characterize patients with extreme reduction in CM; second, to follow those patients who eventually did undergo the procedure and examine possible improvements in CM.

Within the first objective, the efficiency of the TCROM and its associated mean CV (MCV) in differentiating chronic whiplash associated disorders patients from healthy subjects as well as typical from atypical patients, was explored. Cervical motion was measured using the Zebris system in 75 healthy subjects and 101 patients in each of the 6 primary movements. In addition, patients filled the functional Neck Disability Index and personality Symptom Check List questionnaire to examine possible relationships with CM. Total CROM was significantly lower, and the MCV was significantly higher in patients compared to healthy subjects. Age and sex affected TCROM significantly in both groups, whereas MCV remained unaffected. Atypical patients who identified by having an extremely low TCROM of less than 58° (vs an average of approximately 350° in normal and 200° in the patient group) and/or a very low consistency of performance expressed by an MCV higher than 22%, where the cutoffs for both outcome parameters corresponded to 2SDs below and above group means, respectively. Application of these cutoff values resulted in 6% of the patients being classified as atypical. They also scored drastically on the functional and personality scales. Thus, for the first time, it was possible to identify, within the general whiplash patient group, a subgroup characterized by low motor performance, which could, at least partly, result from some psychological involvement. Such patients should therefore benefit from behavioral input.[27]

Regarding the second objective, 40 patients were assessed before and at 2 separate sessions after cervical radiofrequency neurotomy. The evaluation included Neck Disability Index, CM, isometric cervical muscles strength, cervical pressure pain threshold, Symptom Check List as well as subjective self-report of improvement. It was indicated that the procedure had a significant and positive effect on all measured parameters. A case-by-case analysis revealed improvement in 70% of the patients at Test 3. However, using for the first time a TCROM-based SRD of 59.5°,[28] it was indicated that a clinically important change occurred in around 40% of the patients, whereas improvement based on sheer increase in CM took place in 70% of the patients. Notably, subjective rating revealed that more than 80% of the patients were satisfied with the procedure. Interestingly, the relationship between imagined pain and associated variations in CM was highlighted for the first time in a recent, yet unpublished, study involving healthy subjects and patients who have degenerative pathology of the cervical spine.[29] This application may be of help in determination of impairment where there is a serious doubt regarding severity of pain.

Clinical decision making regarding the treatment of patients with neck pain is often based on findings drawn from the clinical examination, the latter being derived from patients' signs and symptoms as opposed to diagnostic imaging.[25] The clinical examination is also used to identify subgroups of patients who are most likely to respond to a particular type of intervention.[30] Within this context, it was reported that the intertester reproducibility of the muscle length and CM were significantly higher in comparison to the reproducibility of findings obtained from other manual assessment techniques.[25]

In a recent article, CM served as a central outcome measure in clinical decision-making algorithm intended for the evaluation and treatment of patients with cervical pain.[31] Limitation in CM also assists in the finer classification of patients with whiplash into subgroups who would have otherwise been collectively defined as grade II according to the Quebec Task Force from 1995.[32] Impaired neck mobility has been introduced as a major criterion in cervicogenic headache. However no significant reductions were revealed in migraine or tension-type headaches.[33-36] Another application of CM relates to the differentiation of the sources of shoulder pain. Patients experiencing shoulder pain may be classified into 4 categories, reflecting the distinction between problems of the shoulder and those of the neck. A simple classification rule has been proposed enabling classification of almost all patients into 4 clusters according to cervical and or shoulder RoM restrictions.[37]

Within the neurological domain, CM is the most elaborated outcome measure in patients with cervical dystonia, before and after therapy with botulinum toxin type A.[38]

Because CM is volitionally controlled, its assessment depends on full patient collaboration. In determination of the degree of impairment, the question whether the patient is indeed putting a maximal effort is therefore of paramount importance, particularly when other objective findings are difficult to obtain. In a series of articles, this issue has been addressed using an experimental paradigm in which subjects were asked to perform at maximal effort and then to feign limitation of to gain financially.[23,39,40] Patients who have whiplash[41] and degenerative changes in the cervical spine[41] were asked, following a standard test, to imagine that they were experiencing a much higher level of pain. Their CM was then measured. Stringent cutoff scores for differentiation between maximal and submaximal performance were determined at 95% level of confidence using the CV of 3 consecutive CM measurements.

Conclusions

Recent years witnessed the introduction of advanced systems into the field of CM measurement. These as well as other simpler yet accurate devices, all distinguished by high accuracy and clinically acceptable reproducibility, have greatly enhanced the power of CM findings. As a result, CM provides a substantial outcome parameter for assessing the level of effort and the severity of motion limitation in cervically involved patients as well as following up their performance during and after conservative or invasive interventions.

References

1. Youdas JW, Carey JC, Garrett TR. Reliability of measurements of cervical spine range of motion—comparison of three methods. Phys Ther 1991;71:98-106.
2. Chibnail JT, Duckero PN, Baumer K. The influence of body size on linear measurements used to reflect cervical range of motion. Phys Ther 1994;74:1134-7.
3. Alaranta H, Hurri H, Heliovaara M, Soukka A, Harju R. Flexibility of the spine: normative values of goniometric and tape measurements. Scand J Rehab Med 1994;26:147-54.
4. Youdas JW, Garrett TR, Suman VJ, Bogard CL, Hallman HO, Carey JR. Normal range of motion of the cervical spine: an initial goniometric study. Phys Ther 1992;72:770-80.
5. Tucci SM, Hichs JE, Gross EG, Campbell W, Danoff J. Cervical motion assessment: A new, simple and accurate method. Arch Phys Med Rehabil 1986;67:225-30.
6. Kuhlman KA. Cervical range of motion in the elderly. Arch Phys Med Rehabil 1993;74:1071-9.
7. Tousigant M, Bellefeuille L, O'Donoughue S, Grahovac S. Criterion validity of the cervical range of motion (CROM) goniometer for cervical flexion and extension. Spine 2000;25: 324-30.

8. Mayer T, Brady S, Bovasson E, Pope P, Gatchel RJ. Noninvasive measurement of cervical tri-planar motion in normal subjects. Spine 1993;18:2191-5.
9. Hoving JL, Pool JJ, Mamern HV, Deville WJLM, Assendelft WJJ, de Vet HCW, de Winter AF, Bouter LM. Reproducibility of cervical range of motion in patients with neck pain. BMC Musculosk Disord 2005;6:59-63.
10. Lantz CA, Chen J, Buch D. Clinical validity and stability of active and passive cervical range of motion with regard to total and unilateral uniplanar motion. Spine, 1999;24:1082-9.
11. Dvorak J, Antinnes JA, Panjabi M, Loustalot D, Bonomo M. Age and gender related normal motion of the cervical spine. Spine 1992;17:s393-8.
12. Feipel V, Rodelet B, Le Pallec JP, Rooze M. Normal global motion of cervical spine: an electrogoniometric study. Clin Biomech 1999;14:462-70.
13. Alund M, Larsson SE. Three dimensional analysis of neck motion, a clinical method. Spine 1990;15:87-91.
14. Trott PH, Pearcy MJ, Ruston SA, Fulton I, Brien C. Three dimensional analysis of active cervical motion: the effect of age and gender. Clin Biomech 1996;11:201-6.
15. Walmsley RP, Kimber P, Culham E. The effect of initial head position on active axial rotation range of motion in two age population. Spine 1996;21:2435-42.
16. Sforza CS, Gracci GP, Fragnito N, Turci M, Ferrario VF. Three-dimensional analysis of active head and cervical spine range of motion: effect of age in healthy male subjects. Clin Biomech 2002;17:611-4.
17. Dvir Z, Prushansky T. Reproducibility and instrument validity of a new ultrasonography-based system for measuring cervical spine kinematics. Clin Biomech 2000;15:658-64.
18. Dvir Z, Werner V, Peretz C. The effect of measurement protocols on cervical range of motion. Physiother Res Int 2002; 7:136-45.
19. Chen J, Solinger AB, Poncet JF, Lantz C. Meta-analysis of normative cervical spine. Spine 1999;24:1571-8.
20. Malmström EM, Karlberg M, Fransson PA, Melander A, Magnusson M. Primary and coupled cervical movements: the effect of age, gender, and body mass index. A 3-dimensional movement analysis of a population without symptoms of neck disorders. Spine 2004;31:E44-E50.
21. Prushansky T, Pevzner Y, Gordon C, Dvir Z. Performance of cervical motion in chronic whiplash patients and healthy subjects: the case of atypical patients. Spine 2006;31:37-43.
22. Beckrman H, Roebroeck ME, Lankhorst GJ, Becker JG, Bezemer PD, Verbeek ALM. Smallest real difference, a link between reproducibility and responsiveness. Qual Life Res 2001;10:571-8.
23. Dvir Z, Prushansky T, Peretz C. Maximal versus feigned active cervical motion in healthy patients. The coefficient of variation as an indicator for sincerity of effort. Spine 2001;26:1680-8.
24. Cagnie B, Cools A, De Loose V, Cambier D, Danneels L. Reliability and normative database of the Zebris cervical range-of-motion system in healthy controls with preliminary validation in a group of patients with neck pain. J Manip Physiol Ther 2007;30:450-5.
25. Cleland JA, Childs JD, Fritz JM, Whitman JM. Interrater reliability of the history and physical examination in patients with mechanical neck pain. Arch Phys Med Rehabil 2006;87: 1388-95.
26. Andersson GBJ, Cocchiarella L. Guides to the evaluation of permanent impairment. 5th ed. AMA Press; 2001.
27. Prushansky T, Pevzner Y, Gordon C, Dvir Z. Cervical radiofrequency neurotomy in chronic whiplash patients: a study of multiple outcome measures. J Neurosurg Spine 2006; 4:365-73.
28. Dvir Z, Gal-Eshel N, Shamir B, Pevzner E, Peretz C, Knoller N. Simulated pain and cervical range of motion in patients with chronic cervical disorders. Pain Res Manage 2004;9: 131-6.
29. Kalron A. Unpublished MSc thesis, Tel Aviv University, 2006.
30. Childs MJD, Fritz JM, Piva SR, Whitman JM. Proposal of a classification system for patients with neck pain. J Orthop Sport Phys Ther 2004;34:686-700.
31. Wang WTJ, Olson SL, Campbell AH, Hanten WP, Gleeson PB. Effectiveness of physical therapy for patients with neck pain. Am J Phys Med Rehabil 2003;82:203-18.
32. Spitzer WO, Skovron ML, Salmi LR. Scientific monograph of the Québec Task Force on Whiplash-Associated Disorders: Redefining "Whiplash" and its management. Spine 1995;20: s1-s73.
33. Sjaastad O, Fredrikson TA, Pfaffenrath V. Cervicogenic headache: diagnostic criteria. Headache 1998;38:442-5.
34. Zwart JA. Neck mobility in different headache disorders. Headache 1997;37:6-11.
35. Jull G, Amiri M, Bullock-Saxton J, Darnell R, Lander C. Cervical musculoskeletal impairment in frequent intermittent headache. Part 1: subjects with single headaches. Cephalalgia 2007;27:793-802.
36. Amiri M, Jull G, Bullock-Saxton J, Darnell R, Lander C. Cervical musculoskeletal impairment in frequent intermittent headache. Part 2: subjects with concurrent headache types. Cephalalgia 2007;27:891-8.
37. Groenier KH, Winters JC, van Schuur WH, De Winter AF, Meyboom-De Jong B. A simple classification system was recommended for patients with restricted shoulder or neck range of motion. J Clin Epidemiol 2006;59:599-607.
38. Gregori B, Agostino R, Bologna M, Dinapoli L, Colosimo C, Accornero N, Berardelli A. Fast voluntary neck movements in patients with cervical dystonia: a kinematic study before and after therapy with botulinum toxin type A. Clin Neurophysiol 2008;119:273-80.
39. Dvir Z, Prushansky T. Cervical circumduction in normal subjects: a study of maximal vs. feigned effort. J Spinal Disord 2001;14:472-8.
40. Dvir Z, Penso-Zabludowski E. The effects of protocol and test situation on maximal vs. submaximal cervical motion: medicolegal implications. Int J Legal Med 2003;117:350-5.
41. Dvir Z, Gal-Eshel N, Shamir B, Prushansky T, Pevzner E, Peretz C. Cervical motion in patients with chronic disorders of the cervical spine: a reproducibility study. Spine 2006;31: E394-9.