Visual Feedback of Bilateral Bite Force to Assess Motor Control of the Mandible in Isometric Condition.

DOI:10.1123/mc.2014-0011

(Article begins on next page)

Motor Control 19 (4) 2015 ; 312-324

DOI: *10.1123/mc.2014-0011*

TITLE

VISUAL FEEDBACK OF BILATERAL BITE FORCE TO ASSESS MOTOR CONTROL OF THE MANDIBLE IN ISOMETRIC CONDITION

AUTHORS

Marco Testa

Department of Neuroscience, Rehabilitation, Ophtalmology, Genetics, Maternal and Child Health – University of Genova – Campus of Savona, Italy

Tommaso Geri

Department of Neuroscience, Rehabilitation, Ophtalmology, Genetics, Maternal and Child Health – University of Genova – Campus of Savona, Italy

Alessio Signori

Department of Health Sciences - Section of Biostatistics; University of Genova, Italy

Silvestro Roatta

Departments of Neuroscience, University of Torino, Torino

Corresponding author:

Marco Testa

Campus Universitario di Savona

Via Magliotto 2- 17100 Savona

Italy

Email: marco.testa@unige.it

Tel: +39 3289213515

Fax: +39 019 860250

ABSTRACT

The assessment of the individual ability of modulating and coordinating the right and left bite force is poorly investigated.

The present study describes a methodology for the assessment of the bilateral control of the biting force and evaluates the test-retest reliability in a sample of 13 healthy subjects. By modulating the intensity and the left/right balance of the biting force, the subject was able to drive a cursor on the screen in order to “reach and hold” targets, randomly generated within the physiological “range of force” of the subject. The average motor performance was evaluated by the Mean cursor-target Distance = 13 ± 5%, the Offset Error = 9 ± 5% and the Standard Deviation of the force vector = 17.7 ± 6.1% (expressed as % of the target). Mean Distance and Standard Deviation indices had acceptable reliability.

This technique improves the characterization of the mandibular motor function and it may have a relevant role for the assessment and rehabilitation of the neuromusculoskeletal disorders affecting the orofacial system.

INTRODUCTION

The function of mastication requires an accurate bite force control to manipulate and break food of different size, shape and hardness. A complex sensory inflow, arising from periodontal receptors and muscle spindles, as well as from mucosal and tongue receptors, contributes to the generation of an effective masticatory pattern and to finely tune the bite force and the mandible movement, according to the size, the hardness and the shape of the food pieces (van der Bilt, Engelen, Pereira, van der Glas, and Abbink, 2006).

The contraction of the masseter muscles, which mainly contributes to occlusal forces, depends on a/the common bilateral neuronal drive that means the right and left masseters are always recruited synchronically in biting tasks (Jaberzadeh, Miles, and Nordstrom, 2006). On the other hand, the ability to modulate right and left masseter contraction and to involve other masticatory muscles like temporalis and medial and lateral pterygoyd, is necessary for the implementation of the different masticatory patterns and their adaptation to changes in hardness and position of food in the mouth (Lund and Kolta, 2006).

Several biomechanical and neuromuscular factors could influence and characterize this complex sensory-motor control which is altered, with different extent, by the presence of pain (Castroflorio, Falla, Wang, Svensson, and Farina, 2012) or as a consequence of neurological disorders like stroke (Schimmel et al., 2011; Schimmel et al., 2013), or Parkinson's disease (Bakke, Stine L. Larsen, Lautrup, and Karlsborg, 2011) or rheumatic diseases (Hiz, Ediz, Ozkan, and Bora, 2012).

Nowadays biofeedback rehabilitation is a widely diffused approach for the therapy of dysfunctions affecting limbs and spine (Dogan-Aslan, Nakipoglu-Yuzer, Dogan, Karabay, and Ozgirgin, 2012; Holtermann, Mork, Andersen, Olsen, and Sogaard, 2010; Varoqui, Froger, Pelissier, and Bardy, 2011) and several devices, mainly oriented to provide the patients with visual target and feedback, are available to support this approach. At the same time, these devices give the therapist useful data about the precision of the movement performed by the patient allowing an objective, quantitative assessment and an ongoing monitoring of the progresses. The measure of force steadiness during isometric contractions, as well as the precision of movement in tracking tasks, have been employed to study the sensory-motor function in the cervical spine (Kristjansson and Oddsdottir, 2010) and in the hand, in particular related to grasp (Blank, Heizer, and von Voss, 2000), and grip in healthy subjects and patients (Kriz, Hermsdorfer, Marquardt, and Mai, 1995; Kurillo, Bajd, and Tercelj, 2004).

In the field of the temporomandibular disorders therapy, the approach is still based on "muscle re-education model" (Moraes Ada, Sanches, Ribeiro, and Guimaraes, 2013) and only recently issues, such as learning and brain plasticity applicable in a rehabilitative perspective, have received attention (Iida et al., 2013). These contributions posed some basis for a future development of rehabilitation programs concerning not only muscles force and joint mobility but also the recovery of the motor control that is often altered by the pathology. To this aim, procedures for the objective and quantitative assessment of the different aspects of the mandibular motor performance are essential.

The complexity of the masticatory system is mainly indirectly and qualitatively evaluated, e.g. by analyzing the extent of comminution of a standard bolus by a finite number of masticatory acts, while direct quantitative measurements are often limited to the maximum voluntary contraction (MVC) of jaw/closing muscles. Although the strength of these muscles is an important aspect of the masticatory system (Koc, Dogan, and Bek, 2010), there is a lack of tools for the clinical assessment of more sophisticated and peculiar motor abilities, like the accuracy of the force output and the possibility to differentiate and coordinate the force produced at the two sides of the mandible.

Aim of the present study is thus to provide an objective and quantitative assessment of these individual motor abilities.

The idea is to combine in a single visual feedback the bilateral monitoring of bite force to engage the subjects in a series of visually guided motor tasks requiring an accurate control of the intensity and the left/right balance of bite force.

Recently, a visual feedback based system has been proposed to assess the individual ability of the subjects to control the jaw movement (Roatta et al., 2011) and to control the unilateral bite force in reaching specific targets (Testa, Rolando, and Roatta, 2011). In these studies, different indicators evaluated the individual motor performance with good reliability. Therefore, we hypothesized that a similar approach could be adopted for the characterization of bilateral coordination of the bite force.

MATERIALS AND METHODS

The experiments were conducted in a laboratory setting, within a standardized testing environment, on 13 healthy subjects (6 Males, age: 24-40 years) recruited among the students of a post-graduate course. Subjects were included if presenting first class occlusion according to Angle's classification, complete dentition, and absence of Temporomandibular Disorders' (TMDs) signs and symptoms, according to the Research Diagnostic Criteria for TMD (Schiffman et al., 2010). This eligibility process was performed by a physical therapist with 15 years of experience in TMDs. Each subject was first informed about the experimental procedure and gave his informed consent to participate. The University of Turin Ethical Committee granted ethical approval for the study.

Force measurement and visual feedback

A bilateral force sensor was assembled based on a couple of film transducers (Flexiforce A201, Tekscan USA) housed in a customized cuff. As previously described (Testa et al., 2011), the cuff is made up of different layers that include two inner metal disks (diameter= 10 mm), which protect each sensor and distribute the clenching pressure over their sensing area, and an external rubber layer that slightly yields under the teeth thereby lowering the load under single cusps and offering improved comfort during clenching. In addition, the sensor presented a graduated handle allowing for its precise repositioning in different sessions. The overall thickness of the cuff was 9 mm and decreased to about 5 mm under teeth pressure during clenching. Ther force signals, from the left and right transducers, were thus simultaneously acquired on a computer (USB-6211 DAQ module, National Instruments) and used as coordinates for the instantaneous position of a cursor on a screen, which provides the subject with a visual feedback of the exerted clenching force.

In particular, the right and left forces corresponded to the x and y coordinates of a Cartesian plane rotated 45 degrees counterclockwise. With this setting, a symmetrically loaded clenching (i.e. left force = right force) results in a vertical upward displacement of the cursor while increased force on the left or right side would deviate the cursor accordingly. The signal acquisition and the visual feedback were developed under LabVIEW (National Instruments).

Experimental protocol

The subject sat on a comfortable chair without head support, with the trunk in an erect posture and natural head position. First, he familiarized with the device, learning to “drive” the cursor on the screen by modulating the total clenching force and its distribution between the left and right side.

Secondly, in analogy to the range of movement (ROM), the *range of force (ROF*) was defined in order to describe the physiological limits of this bilateral isometric contraction. Based on the present setting, these limits correspond to the range of movement of the cursor on the screen. For each subject, the individual ROF was thus constructed as a polygon on the bi-dimensional space defined above, according to the following procedure, also depicted in Figure 1A. While holding in place the bilateral force sensor, the subject was asked to perform a maximal clench on the left side (Ly) while trying to minimize the load on the right side (Lx). This was followed by a maximal contraction of the right side (producing the force Rx on the right side and Ry on the left), and by a maximal bilateral contraction (producing the force BILx on the right side and BILy on the left). Each contraction lasted 3 seconds and was separated from the next by a 1-minute interval. This sequence was repeated two times, separated by 2 minutes of rest. The maximum value in each contraction was considered for the definition of the ROF. The alpha angle (see Figure 1A) was considered as an indicator of the independence of the bite force generated by the two sides.

In order to limit the development of muscle fatigue during the task, a working area was defined equal to the ROF scaled down by 30% (see the polygon in Figures 1B, C and D).

The task consisted in controlling the cursor position (grey trajectory in Figures 1B, C and D) by independently grading the force on the two sides of the jaw, in order to match the position of a target. In each trial 23 targets were subsequently generated, within the working area, according to a uniform probability density function; each target was displayed for 5 seconds and separated from the next by a 5-second resting interval. The trial was repeated other two times, each separated by a 5 minutes interval. The whole sequence was replicated in a second experimental session on the following day.

The individual motor performance was assessed by three indices: Mean Distance (MD), Offset Error (OE) and Standard Deviation of the force vector (SD), all values being computed in the last 3 seconds of target presentation in order to exclude the dynamic phase of the contraction and limit the analysis to the steady state. MD is the average cursor-target distance (Figure 1B), OE is the distance between the average cursor position, i.e., the barycenter of the cursor trajectory, and the target (Figure 1C), while SD is the root mean square of the cursor-barycenter distance (Figure 1D) (Roatta et al., 2011). Given the previously observed dependence of the absolute error on the force level (Testa et al., 2011), all parameters were normalized to the target level (its distance from the origin), and expressed in percentage.

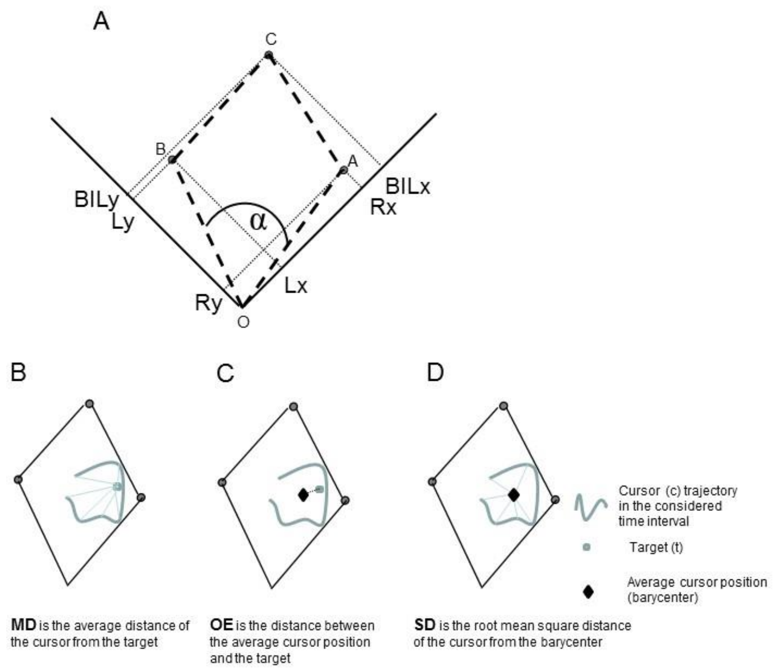

FIGURE 1

Figure 1
A) The *range of force* (ROF) is represented on a Cartesian system (see Methods)
The X axis (on the right) represents the force measured by the right sensor; the Y axis (on the left) the force measured by the left sensor.
The perimeter of the ROF is described by four points (O,A,C,B) where: O corresponds to zero force (rest); A corresponds to the right MVC, reached when asking the subject to exert a maximum force on the right side (Rx, main component) while minimizing force on the left (Ry, associated component); similarly, B corresponds to the left MVC with Ly being the main component and Lx the associated component); C is the point reached when asking the subject to exert a maximal bilateral contraction (BILx, BILy being the forces exerted on right and left side respectively).
B, C, D) Graphical illustrations explaining the meaning of Mean Distance (MD), Offset Error (OE) and Standard Deviation of cursor trajectory (SD), respectively.

While the three indices are mutually dependent, they provide a different functional meaning. SD is an indicator of force unsteadiness: the spread of the cursor trajectory around its barycenter irrespective of the target (and?) can be a measure of *precision*; OE indicates whether there is an offset between the average cursor position and the target and it is a measure of *accuracy*. MD is an overall matching error index which depends on both OE and SD. An intuitive representation of these concepts is exemplified in Figure 2.

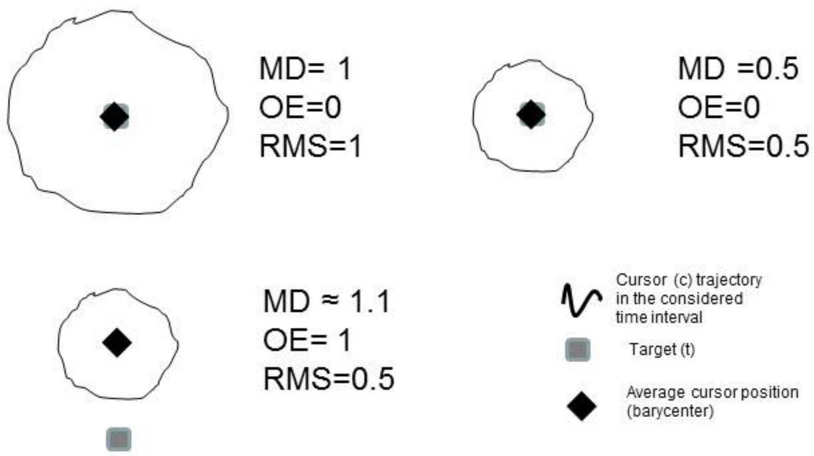

FIGURE 2

Figure 2.Comparison of the indications provided by the three indices MD, OE and SD, in three hypothetical examples, in which a circular cursor trajectory has been assumed.

Statistics

All the data of the exercises (the sequence of targets, and the two force signals) were saved to allow for offline elaboration.

Descriptive analysis of the ROF included the comparison between the left and the right MVC in terms of ipsi- and contralateral forces, the alpha angle and bilateral MVC. A linear regression analysis was conducted on the data from the first session to investigate the concurrent validity of MD, OE and SD. A statistical analysis, to investigate any learning effect, was performed with a two-way multivariate ANOVA for repeated measures with DAY (two levels) and TRIAL (three levels) as factors. The test-retest reliability of measurement was assessed using the second and third trial of the first session; the first trial was excluded being possibly affected by a learning phase (Testa et al., 2011). The Intraclass Correlation Coefficient ($ICC_{agreement}2,1$) was used to assess the relative reliability and it was considered acceptable when above 0.70. The Standard Error of Measurement (SEM), obtained from the root square of mean squared error of a repeated measures ANOVA, and the mean difference between the second and the third trial of the first session with associate Bland and Altman's 95% Limits of Agreement (LOA), were used to estimate absolute reliability. A log-transformation was applied to normalize distribution of data in order to perform the statistical analyses mentioned above.

RESULTS

The subjects easily understood how to drive the cursor on the screen and how to outline the ROF. The dimension of the ROF exhibited a large inter-subject variability: mean value of bilateral MVC (= BILx+BILy, as defined in Figure 1A) was 29.45 ± 8.74 kg and the average alpha angle was 42.4 ± 17.9 deg (range: 21.8 - 60.6 deg).

When asked to exert unilateral MVC, all subjects delivered a variable amount of force also on the contralateral side. During left and right MVC, the force exerted on the ipsilateral side was on average Ly = 12.9 ± 4.4 kg and Rx = 14.8 ± 4.6 kg and on the contralateral side Lx = 5.6 ± 2.8 kg and Ry = 5.6 ± 2.9 kg, respectively. On average contralateral force was 40.6 ± 15.5% of ipsilateral force with no significant difference between left and right MVC (equal to 42.10 ± 15.31 % of main component). The total force measured during unilateral MVC (ipsilateral+contralateral) was 20.09 ± 6.22 kg.

For MD ($F_{[1;12]} = 12.88$; p= 0.004), OE ($F_{[1;12]} = 8.85$; p= 0.012) and SD ($F_{[1;12]} = 9.63$; p = 0.009) a dependency with the session (first/second day) but not with the trials ($F_{[2;11]} = 1.56$; p= 0.25 for MD; $F_{[2;11]} = 2.08$; p= 0.17 for OE; $F_{[2;11]} = 0.48$; p = 0.63 for SD) was detected, indicating a learning effect taking place between the two sessions. The interaction between sessions and trial was not significant ($F_{[2;11]} = 1.49$; p= 0.27 for MD; $F_{[2;11]} = 0.88$; p= 0.44 for OE; $F_{[2;11]} = 1.83$; p = 0.21 for SD) (Figure 3).

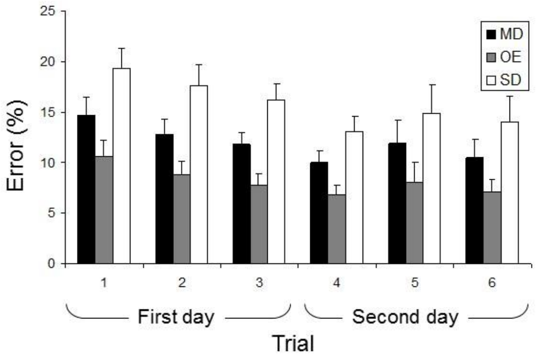

FIGURE 3

Figure 3
Motor performance expressed by Mean distance (MD), Offset error (OE) and Standard Deviation of the trajectory (SD) in the 6 repetitions of the task. Each bar represents the average value (n = 13 subjects) of the average performance in a given task (n= 23 targets). A significant improvement between 1st and 2nd session is observed (see Results).

The values of MD, OE and SD, expressed as percentage of the target force, averaged over the three trials of the first session, were 13 ± 5%, 9 ± 5% and 17.7 ± 6.1%, respectively, while in the second session were 11 ± 6% for MD, 7 ± 5% for OE and 14.0 ± 7.4% for SD.

The two errors MD and OE exhibited a good correlation (r = 0.97; p < 0.001) without showing a dependence on the alpha angle (MD: r = 0.20; OE: r = 0.14) (Figure 4A). Conversely, SD neither showed a high correlation with MD (r= 0.07, Fig. 4B) nor with OE (r=0.15).

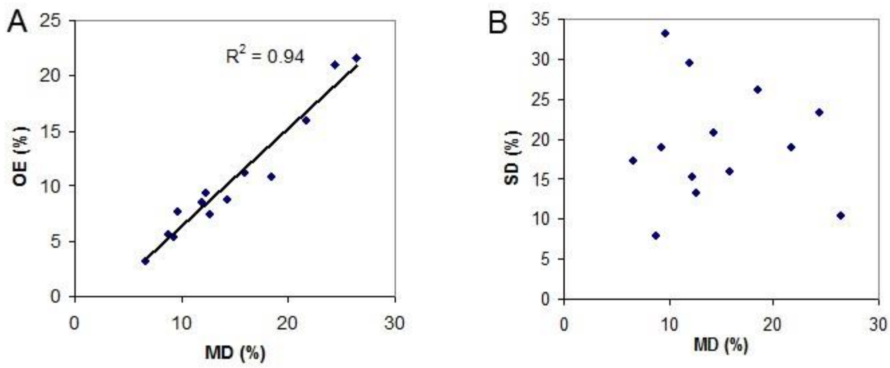

FIGURE 4

Figure 4
Scatter plots of Offset Error (OE) vs. Mean Distance (MD) (A) and of Standard Deviation (SD) vs. MD (B). Note the high correlation between OE and MD

Regarding the test-retest reliability, ICC was 0.78 (95 % CI: 0.43 – 0.93) for MD, 0.66 (95%

CI: 0.20 – 0.88) for OE and 0.78 (95% CI: 0.24 – 0.93) for SD. SEM, expressed as percentage, revealed an error of 22 % in MD, of 35 % in OE and of 21% for SD.

For MD, LOA ranged from -8.1 to 6 % with a mean difference of -1.1% (Figure 5, A). In OE LOA ranged from -8.5 to 6.5% with a mean difference of -1% (Figure 5, B) and in SD (Figure 5, C) ranged from -12.8 to 9.8 % with a mean difference of -1.5%.

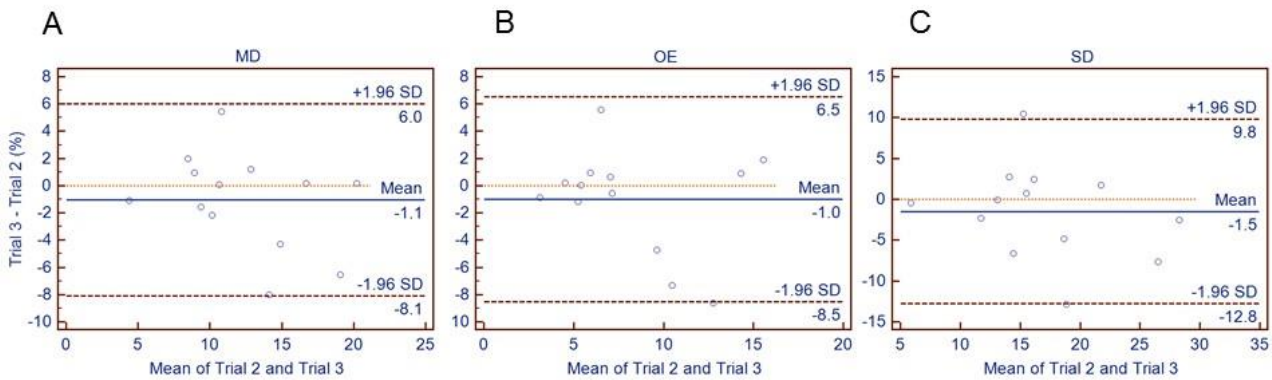

FIGURE 5

Figure 5
A – Limits of Agreement for MD; B – Limits of Agreement for OE; C – Limits of Agreement for SD

DISCUSSION

In this paper an innovative system is proposed which 1) combines in a single visual feedback the bilaterally measured biting force and 2) provides an objective assessment of the bilateral force control of the mandible by engaging the subject in an intuitive "reach-and-hold" type of task, performed in isometric condition.

Biting force is usually assessed by a single force transducer either located unilaterally or in mid-sagittal position. Recently, two different approaches were implemented. Hellmann et al. (2011) bilaterally loaded the mandible with two inter-connected water-filled pads which allowed for active balancing of bite force but they were connected to a single pressure transducer whose measurement was fed back to the subject by means of a numerical display, thus the force exerted on the two sides of the mandible was not distinctly assessed. Rues, Lenz, Turp, Schweizerhof, and Schindler (2008) and Schindler, Rues, Turp, Schweizerhof, and Lenz (2005) implemented instead a sophisticated analysis of the biting force based on a multi-point measurement. The vectorial representation of the measured bite force was provided to the subject by means of a bar indicating force amplitude and a planar representation of the two angles defining the vector orientation.

By relying on two force transducers, a more intuitive, bidimensional representation of bite force was here implemented (Fig. 1A). This type of visual feedback was recently employed in a kynesiograph-based system to monitor and assess precision of free mandible movements in a real reach-and-hold task (Roatta et al., 2011). In that study, adequate mandible movements had to be performed in order to reach the displayed targets with the cursor (reflecting the lower incisors position on the frontal plane), and the individual performance was assessed by means of the same error indices (MD, OE, SD) expressed in millimeters (Roatta et al., 2011). These two studies support the idea that this kind of visual feedback provides an effective cue for visually driving, in a bidimensional space, both the mandible movement (on the frontal plane) or the combination of left and right biting forces. In the present study this was made possible by introducing the new concept of *range of force* (ROF), derived from the well established *range of motion* (ROM). The ROM of the mandible is described as the largest possible displacement of the lower incisors with respect to the skull, and it is known as the Posselt's envelope (Posselt, 1958). When dealing with force rather than movement the physiological limits are usually represented by the monodimensional range [0-MVC]. The mandible is, however, a complex joint in which biting force is jointly produced by jaw elevator muscles from the left and the right side, which, to a certain extent, can be independently activated. In fact, when trying to bite with the left side only, some force is involuntarily exerted also on the right side, and vice versa. For this reason, the set of physiological combination of left and right biting forces can be represented on a Cartesian plane by the points laying within the polygon of Figure 1A, as described in "Materials and Methods".

The capacity of independently controlling left and right biting forces may be an important variable to characterize the individual motor control of the mandible and it can be assessed from the analysis of the ROF geometry. In particular, the alpha angle can be considered a good indicator of this capacity. Its maximum theoretical value of 90 deg would denote the capacity of exerting maximal force with one side while leaving the opposite side completely unloaded while the minimum value of 0 deg would mean that the subject cannot unbalance the force between the two sides and the force on the left side is always equal to the right. We here observed a large inter-individual variability of the alpha angle (range: 21.8 – 60.6 deg). To what extent the alpha angle may be correlated to functional aspects or be affected by pathological conditions needs to be elucidated in future studies.

The present work extends the result of a previous study in which the control of jaw-closing force was assessed during unilaterally-loaded isometric contractions and indices of performance like MD, OE and SD were proposed and validated (Testa et al., 2011). These indices have been here redefined for the bi-dimensional space, and it is interesting to compare the results of the two studies. It appears that the increased complexity of the bilateral task caused a slight increase in the error indices as compared to the unilateral task: MD = 13 % and OE = 9 % and SD= 18 % versus MD = 10 %, OE = 6.2 % and SD= 18 % (Testa et al., 2011). In addition, while in the unilateral exercise MD was correlated with both OE (r^2= 0.85) and SD (r^2=0.76) in the present study it exhibited a good correlation with OE (r^2= 0.94) but not with SD (r^2=0.004). In principle, the global error index MD is affected by both precision (related to SD) and accuracy (OE) and, as illustrated in Fig 2B and C, the dependence of MD on SD decreases when OE increases. Thus, the high and exclusive correlation of MD with OE here observed suggests that the factor limiting the motor performance, as assessed by MD, is the increased difficulty in the coordination of the right and left masticatory muscles to drive the cursor over the target in the bidimensional, as compared to the monodimensional task, rather than the delivery of a bilaterally steady force. However, in both studies, no significant change in the performance was observed within the same session, while a significant improvement was found in the second with respect to the first session. The between-session difference is interpreted in terms of a learning effect, which has been shown to occur overnight in visuomotor tasks (Landsness et al., 2009). More recently, learning effects have been specifically investigated in jaw motor skills. It has been observed that the jaw motor system is concerned with motor learning, both in the short (Iida et al., 2013) and in the long term (Hellmann et al., 2011). Iida et al. (2013), by a visual feedback based task, showed higher reduction in variability of bite force, compared to pinch force, suggesting that the jaw motor system may be more prone to motor learning than the hand. Being the orofacial system usually governed in the absence of visual feedback, one could speculate that the addition of this sensory channel widens the possibilities of motor improvement. Hellmann et al. (2011) reported the occurrence of long term learning in coordination tasks of bilateral bite force while Svensson, Romaniello, Arendt-Nielsen, and Sessle (2003) demonstrated cortical plasticity in response to tongue protrusion training. Since a high number of repetitions are needed in order to achieve a consolidation of the performance in a motor task (Song, 2009), the between-session improvement observed in the present case is probably the result of a short-term learning without retention.

The test-retest reliability assessed in the first session was acceptable for the MD and SD indices, while the OE index did not reach the predefined threshold. Probably, the poor reliability of OE index with the large confidence interval could be attributed to the small sample size, because the other two indices performed well.

In a recent study, van der Bilt, Tekamp, van der Glas, and Abbink (2008) found bilateral MVC to be 30% larger than unilateral MVC. In the present study the bilateral MVC was 112% of the ipsilateral component of unilateral MVC and 51% larger than the total unilateral MVC (ipsi + contralateral component). This difference could be attributed to the characteristics of both the force transducer employed in the present study (both sides of the mandible were simultaneously loaded) and of the task (the subject was asked to perform a maximal clench on one side while trying to minimize the load on the opposite side). It is well known that both masseter muscles contract even when the mandible is unilaterally loaded (van der Bilt et al., 2008). Thus, in the case of unilateral load, the whole jaw-closing force (generated by left and right muscles) is collected by a single force sensor. When the subject performs the unilateral MVC on a bilaterally loaded mandible, the contralateral sensor collects part of the clenching force. Moreover, the attempt to minimize the force on the contralateral side most likely requires a redefinition of the motor strategy possibly including a submaximal contraction of ipsilateral muscles. It follows that the measured force value strongly depends on the different methodological aspects.

Although the bilateral exercise proposed in the present study does not reproduce the complex motor pattern of mastication, the possibility to engage the subject in adjusting different force levels of the two side of the mandible while assessing his/her performance is a potentially useful tool in rehabilitation. Biofeedback based rehabilitation programs have been used with encouraging results to treat limb and spine sensorimotor impairments, due to neurological pathologies or musculoskeletal disorders (Dogan-Aslan et al., 2012; Holtermann et al., 2010; Varoqui et al., 2011) while there are no specific sensorimotor rehabilitation programs nor quantitative systems to evaluate performance and alterations of mandibular motor control, in clinical settings. Lodha, Coombes, and Cauraugh (2012) implemented a motor task similar to the one here proposed to assess bimanual isometric force control and coordination in stroke patients and suggested it could serve as a basis for rehabilitation protocols. Intuitive visual feedback of the force exerted on the left and right sides of the mandible may thus provide the basis for building up specific rehabilitation protocols aimed at restoring coordination and control of jaw muscles.

CONCLUSION

An intuitive visual feedback system was presented which engaged the subject in a fine and independent control of left and right bite force. The concept of *range of force* was introduced to univocally describe the bi-dimensional force domain which accounts for the individual muscle strength as well as the extent of left/right independence. The results provided a first indication of the motor performance in healthy subjects and of the reliability of the assessment. Given the easiness of implementation of the bilateral force measurement and of the execution of the motor task, this system is potentially suited to be introduced in the clinical setting to support the characterization of disorders involving the masticatory system as well as a tool for training and functional rehabilitation of the temporomandibular joint. In this respect, investigations on TMD patients are needed to test the efficacy of this approach.

ACKNOWLEDGMENTS

We acknowledge the contribution of Mara Rolando in collecting the experimental data and implementing the acquisition software.

This work was supported by grants from Regione Piemonte and Università di Torino.

References

Bakke, M., Stine L. Larsen, Lautrup, C., & Karlsborg, M. (2011). Orofacial function and oral health in patients with Parkinson' ™ s disease. *Eur J Oral Sci, 119*(1), 27-32.

Blank, R., Heizer, W., & von Voss, H. (2000). Development of externally guided grip force modulation in man. *Neurosci Lett, 286*(3), 187-190.

Castroflorio, T., Falla, D., Wang, K., Svensson, P., & Farina, D. (2012). Effect of experimental jaw-muscle pain on the spatial distribution of surface EMG activity of the human masseter muscle during tooth clenching. *J Oral Rehabil, 39*(2), 81-92. Pubmed doi: 10.1111/j.1365-2842.2011.02246.x

Dogan-Aslan, M., Nakipoglu-Yuzer, G. F., Dogan, A., Karabay, I., & Ozgirgin, N. (2012). The effect of electromyographic biofeedback treatment in improving upper extremity functioning of patients with hemiplegic stroke. *J Stroke Cerebrovasc Dis, 21*(3), 187-192. Pubmed doi: 10.1016/j.jstrokecerebrovasdis.2010.06.006

Hellmann, D., Giannakopoulos, N. N., Blaser, R., Eberhard, L., Rues, S., & Schindler, H. J. (2011). Long-term training effects on masticatory muscles. *J Oral Rehabil, 38*(12), 912-920. Pubmed doi: 10.1111/j.1365-2842.2011.02227.x

Hiz, O., Ediz, L., Ozkan, Y., & Bora, A. (2012). Clinical and magnetic resonance imaging findings of the temporomandibular joint in patients with rheumatoid arthritis. *J Clin Med Res, 4*(5), 323-331. Pubmed doi: 10.4021/jocmr1084w

Holtermann, A., Mork, P. J., Andersen, L. L., Olsen, H. B., & Sogaard, K. (2010). The use of EMG biofeedback for learning of selective activation of intra-muscular parts within the serratus anterior muscle: a novel approach for rehabilitation of scapular muscle imbalance. *J Electromyogr Kinesiol, 20*(2), 359-365. Pubmed doi: 10.1016/j.jelekin.2009.02.009

Iida, T., Komiyama, O., Obara, R., Baad-Hansen, L., Kawara, M., & Svensson, P. (2013). Influence of visual feedback on force-EMG curves from spinally innervated versus trigeminally innervated muscles. *Arch Oral Biol, 58*(3), 331-339. Pubmed doi: 10.1016/j.archoralbio.2012.12.005

Jaberzadeh, S., Miles, T. S., & Nordstrom, M. A. (2006). Organisation of common inputs to motoneuron pools of human masticatory muscles. *Clin Neurophysiol, 117*(9), 1931-1940. Pubmed doi: 10.1016/j.clinph.2006.05.013

Koc, D., Dogan, A., & Bek, B. (2010). Bite force and influential factors on bite force measurements: a literature review. *Eur J Dent, 4*(2), 223-232.

Kristjansson, E., & Oddsdottir, G. L. (2010). "The Fly": a new clinical assessment and treatment method for deficits of movement control in the cervical spine: reliability and validity. *Spine (Phila Pa 1976), 35*(23), E1298-1305. Pubmed doi: 10.1097/BRS.0b013e3181e7fc0a

Kriz, G., Hermsdorfer, J., Marquardt, C., & Mai, N. (1995). Feedback-based training of grip force control in patients with brain damage. *Arch Phys Med Rehabil, 76*(7), 653-659.

Kurillo, G., Bajd, T., & Tercelj, M. (2004). The effect of age on the grip force control in lateral grip. *Conf Proc IEEE Eng Med Biol Soc, 6*, 4657-4660. Pubmed doi: 10.1109/iembs.2004.1404290

Landsness, E. C., Crupi, D., Hulse, B. K., Peterson, M. J., Huber, R., Ansari, H., . . . Tononi, G. (2009). Sleep-dependent improvement in visuomotor learning: a causal role for slow waves. *Sleep, 32*(10), 1273-1284.

Lodha, N., Coombes, S. A., & Cauraugh, J. H. (2012). Bimanual isometric force control: asymmetry and coordination evidence post stroke. *Clin Neurophysiol, 123*(4), 787-795. Pubmed doi: 10.1016/j.clinph.2011.08.014

Lund, J. P., & Kolta, A. (2006). Generation of the central masticatory pattern and its modification by sensory feedback. *Dysphagia, 21*(3), 167-174. Pubmed doi: 10.1007/s00455-006-9027-6

Moraes Ada, R., Sanches, M. L., Ribeiro, E. C., & Guimaraes, A. S. (2013). Therapeutic exercises for the control of temporomandibular disorders. *Dental Press J Orthod, 18*(5), 134-139.

Posselt, U. (1958). Range of movement of the mandible. *J Am Dent Assoc, 56*(1), 10-13.

Roatta, S., Rolando, M., Notaro, V., Testa, M., Bassi, F., & Passatore, M. (2011). Objective assessment of mandibular motor control using a 'reach-and-hold' task. *J Oral Rehabil, 38*(10), 737-745. Pubmed doi: 10.1111/j.1365-2842.2011.02215.x

Rues, S., Lenz, J., Turp, J. C., Schweizerhof, K., & Schindler, H. J. (2008). Forces and motor control mechanisms during biting in a realistically balanced experimental occlusion. *Arch Oral Biol, 53*(12), 1119-1128. Pubmed doi: 10.1016/j.archoralbio.2008.06.006

Schiffman, E. L., Ohrbach, R., Truelove, E. L., Tai, F., Anderson, G. C., Pan, W., . . . Look, J. O. (2010). The Research Diagnostic Criteria for Temporomandibular Disorders. V: methods used to establish and validate revised Axis I diagnostic algorithms. *J Orofac Pain, 24*(1), 63-78.

Schimmel, M., Leemann, B., Herrmann, F. R., Kiliaridis, S., Schnider, A., & Muller, F. (2011). Masticatory function and bite force in stroke patients. *J Dent Res, 90*(2), 230-234. Pubmed doi: 10.1177/0022034510383860

Schimmel, M., Leemann, B., Schnider, A., Herrmann, F. R., Kiliaridis, S., & Muller, F. (2013). Changes in oro-facial function and hand-grip strength during a 2-year observation period after stroke. *Clin Oral Investig, 17*(3), 867-876. Pubmed doi: 10.1007/s00784-012-0769-2

Schindler, H. J., Rues, S., Turp, J. C., Schweizerhof, K., & Lenz, J. (2005). Activity patterns of the masticatory muscles during feedback-controlled simulated clenching activities. *Eur J Oral Sci, 113*(6), 469-478. Pubmed doi: 10.1111/j.1600-0722.2005.00249.x

Song, S. (2009). Consciousness and the consolidation of motor learning. *Behav Brain Res, 196*(2), 180-186. Pubmed doi: 10.1016/j.bbr.2008.09.034

Svensson, P., Romaniello, A., Arendt-Nielsen, L., & Sessle, B. J. (2003). Plasticity in corticomotor control of the human tongue musculature induced by tongue-task training. *Exp Brain Res, 152*(1), 42-51. Pubmed doi: 10.1007/s00221-003-1517-2

Testa, M., Rolando, M., & Roatta, S. (2011). Control of jaw-clenching forces in dentate subjects. *J Orofac Pain, 25*(3), 250-260.

van der Bilt, A., Engelen, L., Pereira, L. J., van der Glas, H. W., & Abbink, J. H. (2006). Oral physiology and mastication. *Physiol Behav, 89*(1), 22-27. Pubmed doi: 10.1016/j.physbeh.2006.01.025

van der Bilt, A., Tekamp, A., van der Glas, H., & Abbink, J. (2008). Bite force and electromyograpy during maximum unilateral and bilateral clenching. *Eur J Oral Sci, 116*(3), 217-222. Pubmed doi: 10.1111/j.1600-0722.2008.00531.x

Varoqui, D., Froger, J., Pelissier, J. Y., & Bardy, B. G. (2011). Effect of coordination biofeedback on (re)learning preferred postural patterns in post-stroke patients. *Motor Control, 15*(2), 187-205.