MASTICATORY MUSCLE AND JOINT FORCES DURING CLENCHING BASED ON SIMULTANEOUS FORCE AND EMG MEASUREMENT

S. Rues*, H.J. Schindler*, J.C. Türp**, K. Schweizerhof***, J. Lenz*

* Research Group Biomechanics, University of Karlsruhe, Karlsruhe, Germany
** Dept. of Reconstructive Dentistry, Dental School, University of Basel, Switzerland
*** Institute of Mechanics, University of Karlsruhe, Karlsruhe, Germany

stefan.rues@ifm.uni-karlsruhe.de

Abstract: In ten healthy test persons the EMG activities of the essential masticatory muscles and the intraorally transferred, feedback-controlled resultant force have been measured simultaneously for 19 motor tasks at different magnitudes simulating clenching. Additionally, for all test persons 3D-models of the musculature were reconstructed from magnetic resonance tomograms. The aim of the study was to identify the associated activation patterns, the intrinsic muscle stress and the muscle forces using a linear as well as a non-linear force law, and to calculate the joint reaction forces. On the basis of this information motor tasks leading to high joint forces might possibly be identified. In this contribution the results are presented exemplarily for two test persons.

Introduction

The human masticatory system consists of twelve essential muscles connecting the mandible with the maxilla. Each muscle can generate a force vector with an a priori unknown magnitude but a line of action which can approximately be constructed from its geometry. For the joint forces, however, the magnitude as well as the line of action are unknown. This means that there are 12 (muscle forces) + 6 (joint force components) = 18 unknown parameters in comparison to 6 equilibrium equations. Therefore, the system is highly redundant, i.e., a specific resultant force can be generated by an infinite variety of activation patterns. For this reason, aside of certain optimization methods using arbitrarily chosen target functions, only a simultaneous measurement of all muscular EMG activities and the resultant force between the lower and upper jaw can reveal the actual situation.

Materials and Methods

To date, no measured data is available from experiments in which the activities of all masticatory muscles and the resultant force have been recorded simultaneously. This complete knowledge is, however, indispensable to determine the direction and amount of the reaction forces transferred to the condyles.

For that purpose, in ten healthy male subjects (average age: 29 ± 2.6 years) the intraoral force transfer and the electromyographic activities of the masseter, anterior and posterior temporalis, medial and lateral pterygoid, and anterior digastric were simultaneously recorded in simulated clenching tasks during the generation of various resulting force vectors. A feedback system enabled the test persons to perform 19 specific clenching tasks (circumferential angle φ = 0°, 60°, 90°, 180°, 270°, 300°; cranial angle θ = 0°, 20°, 40°, 60° with respect to the normal z' on the occlusal plane) at different magnitudes of the resultant force F_{res} (cf. Fig. 1). The centrally transmitted resultant force was determined with an intraoral measuring device illustrated in Fig. 1 (bearing pin device equipped with strain gauges and fixed on custom made metal splints).

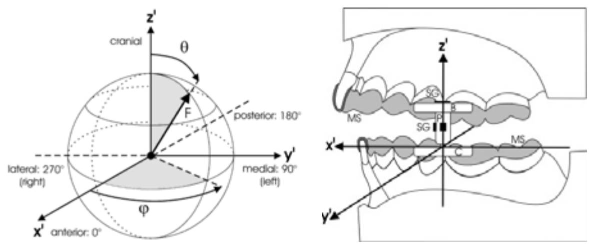

Figure 1: Coordinate system used for the force measurement device (x',y'-plane corresponds to the occlusal plane) with angles φ and θ

Bipolar surface electrodes were employed to measure bilaterally the electrical activities U_i of the masseter, anterior temporalis, posterior temporalis, and anterior digastric, whereas bilateral bipolar wire electrodes, inserted by a needle, recorded the electrical muscle activity of the medial and lateral pterygoid muscles. For special motor tasks also the maximum electrical activities $U_{max,i}$ of all muscles were determined. The experimental particulars are described in detail in [1]. Additionally, for each test person a 3D-model of the musculature (Fig. 2) was constructed using horizontal and frontal magnetic resonance tomograms (MRT) which also served to identify the Frankfort horizontal

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and the occlusal plane as well as the position of the bearing pin. From these models the lines of action (regression lines through the centers of cross-sectional areas perpendicular to the muscle orientation; cf. Fig. 2) and the physiological cross-sectional areas $A_i = V_i/l_f$ (V_i: volume of the contractile tissue of the muscle) were finally acquired using the values for the volumetric portion of the contractile tissue and fibre bundle length l_f as given in [2] .

In the following, the x,y-plane is chosen parallel to the Frankfort horizontal plane with the y-axis coinciding with the axis connecting the centers of the condyles, and the x-axis directed frontally in the midsaggital plane (cf. Fig. 2).

Weijs and Hillen [3] assumed that under static circumstances the maximum force of a muscle is proportional to its physiological cross-section: $F_{max,i} = P \cdot A_i$, where P is the so-called intrinsic stress, indicating the maximum force which can be generated by a muscle fibre bundle with a cross-section of 1 mm^2.

For pennated muscles (pennation angle α_i) this relation must be corrected by the factor $\cos\alpha_i$ which accounts for the fact that only part of the total force acts in the muscle orientation (equ. (1)).

With a chosen law relating the force F_i to the electrical activity U_i (equ. (2)), and the assumption that each joint force intersects the center of its condyle, the intrinsic stress P can be calculated using the balance of momen-tum with respect to the y-axis (equ. (3)). Once P is known, all muscle forces can be specified according to the linear or non-linear force law, respectively.

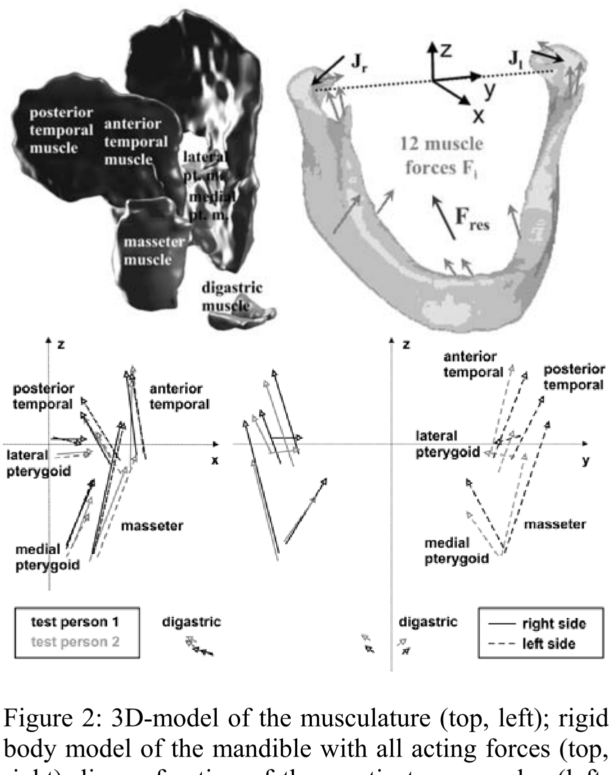


Figure 2: 3D-model of the musculature (top, left); rigid body model of the mandible with all acting forces (top, right); lines of action of the masticatory muscles (left: saggital view, right: frontal view) in a slightly opened jaw position (due to the measurement device) under homogeneous activation (bottom). The length of the spatial vectors corresponds to A_i.

On the basis of a rigid body model (cf. Fig. 2) the remaining five balance equations can be used to determine the components of the left and right joint reaction forces J_l and J_r in x- and z-direction according to equations (3) – (7). Here r_x, r_y, r_z denote the lever arms with respect to the coordinate axes. Tensile forces can not be transferred to the condyles which is expressed by the conditions (8).

$F_{max,i} = P \cdot A_i \cdot \cos\alpha_i$	(1)
linear force law: $\frac{F_i}{F_{max,\,i}} = \frac{U_i}{U_{max,\,i}} = f_1(U_i)$ non-linear force law: $\frac{F_i}{F_{max,\,i}} = c_1\left(\frac{U_i}{U_{max,\,i}}\right)^2 + c_2\left(\frac{U_i}{U_{max,\,i}}\right) = f_2(U_i)$ $f_{1/2}(0) = 0 \quad , \quad f_{1/2}(1) = 1$	(2)
$\sum M_y = P \cdot \sum_{i=1}^{12} A_i \cdot \cos\alpha_i \cdot (r_{z,\,i} \cdot F_{x,\,i} - r_{x,\,i} \cdot F_{z,\,i})$ $+ r_{z,res} \cdot F_{x,res} - r_{x,res} \cdot F_{z,res} = 0$ $P = \frac{-r_{z,\,res} \cdot F_{x,\,res} + r_{x,\,res} \cdot F_{z,\,res}}{\sum A_i \cdot \cos\alpha_i \cdot (r_{z,\,i} \cdot F_{x,\,i} - r_{x,\,i} \cdot F_{z,\,i})}$	(3)
$\vec{J}_{total} = \vec{J}_r + \vec{J}_l = -\vec{F}_{res} - \sum \vec{F}_i$ $\vec{J}_{r\,/\,l} = J_{x,\,r/l} \cdot \vec{e}_x + J_{y,\,r/l} \cdot \vec{e}_y + J_{z,\,r/l} \cdot \vec{e}_z$	(4)
$J_{x,\,r} = \frac{r_{y,\,Jl} \cdot J_{x,\,total} - \sum M_{z,\,i} - M_{z,\,res}}{r_{y,\,Jl} - r_{y,\,Jr}}$ with $M_z = r_x \cdot F_y - r_y \cdot F_x$	(5)
$J_{z,\,r} = \frac{r_{y,\,Jl} \cdot J_{z,\,total} + \sum M_{x,\,i} + M_{x,\,res}}{r_{y,\,Jl} - r_{y,\,Jr}}$ with $M_x = r_y \cdot F_z - r_z \cdot F_y$	(6)
$J_{x,\,l} = J_{x,\,total} - J_{x,\,r} \qquad J_{z,\,l} = J_{z,\,total} - J_{z,\,r}$	(7)
$J_{y,\,r} = J_{y,\,total}$ and $J_{y,\,l} = 0$ if $J_{y,\,total} \le 0$ $J_{y,\,l} = J_{y,\,total}$ and $J_{y,\,r} = 0$ if $J_{y,\,total} > 0$	(8)

Results

Due to lack of space, only the results for two test persons are presented in this work. Table 1 comprises the muscle volumes gained from 3D-models, and the corresponding cross-sectional areas.

Table 1: Muscle volumes and physiological cross-sectional areas of the two test persons

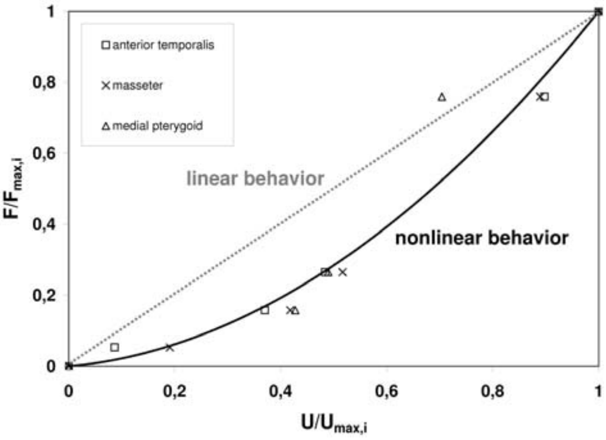
test person	muscle	V_i [cm^3]		A_i [cm^2]	
		right	left	right	left
1	masseter	35.2	35.6	13.5	13.7
	ant. temp.	26.0	27.4	8.5	8.9
	post. temp.	18.4	23.5	6.0	7.7
	medial pt.	13.3	13.3	7.8	7.8
	lateral pt.	10.5	8.5	4.3	3.5
	digastric	4.2	2.7	1.9	1.2
2	masseter	28.0	28.5	10.7	11.0
	ant. temp.	26.8	23.0	8.7	7.5
	post. temp.	14.2	14.7	4.7	4.8
	medial pt.	9.3	9.6	5.5	5.7
	lateral pt.	10.3	10.3	4.3	4.3
	digastric	2.3	2.2	1.1	1.0

All described motor tasks were performed with magnitudes of F_{res} = 50 N and F_{res} = 150 N. The task with vertical resultant force (θ = 0°) was additionally performed with F_{res} = 250 N and under maximum voluntary force of the test persons. The activation pattern for this task does not change significantly [1] with increasing magnitude of the resultant force, i.e., a doubling of the resultant force leads to a doubling of all muscle forces. During this task only the anterior temporal, the masseter, and the medial pterygoid are notedly activated. The measured data for these muscles was used to compute the constants c_1 and c_2 of the non-linear force law for which a polynomial of second order was chosen (equ. (2)). Subsequently, this force law was applied to all muscles under all tasks and the results compared with those of the linear force law. Fig. 3 displays the measured data and the computed non-linear force law (least square fit) for both test persons. The coefficients amounted to $c_1 = 0.8631$ and $c_2 = 0.1369$ for the first, and to $c_1 = 0.8862$ and $c_2 = 0.1138$ for the second test person.

Table 2 presents for both test persons the mean as well as the minimal and maximal values for the intrinsic muscle stress P as calculated on the basis of the linear and non-linear relations shown in Fig. 3. These values are displayed for the following cases: Purely vertical clenching tasks (a) which were exclusively used to determine the non-linear force law; protrusive tasks (b); retrusive tasks (c); and all tasks (d) including those with $\varphi \neq 0°$ and $\varphi \neq 180°$ which are not separately listed in the table.

Naturally, the values for purely vertical clenching are the most reliable ones, because this task was performed for a larger number of force magnitudes including maximum voluntary clenching. Moreover, during this task most muscles are homogeneously activated. In literature [3], the value P = 0.37 N/mm^2 is found for maximum voluntary clenching. In this case ($U_i/U_{max,i} \rightarrow 1$) the choice of a special force law is irrelevant (only minor deviations between different force laws) because merely a single point near $U_i/U_{max,i} = 1$, $F_i/F_{max,i} = 1$ is considered. In this study the corresponding values are found as P = 0.30 N/mm^2 and P = 0.33 N/mm^2 in the linear case and as P = 0.35 N/mm^2 and P = 0.43 N/mm^2 in the non-linear case for test persons 1 and 2, respectively. These results are in satisfactory agreement with the value P = 0.37 N/mm^2 in [3].

It becomes clear from Table 2 that for the linear force law the values found for the intrinsic muscle stress P, are throughout lower than those for the non-linear law.



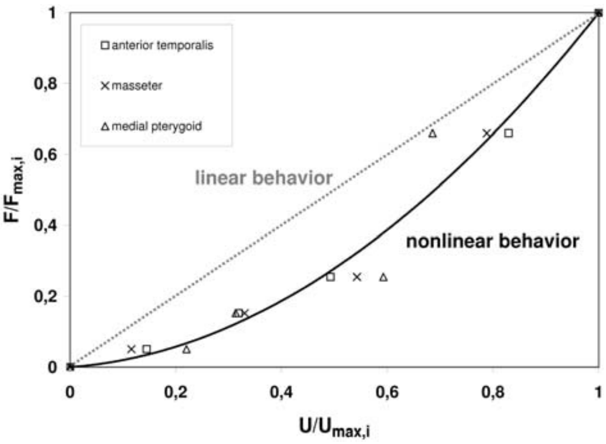
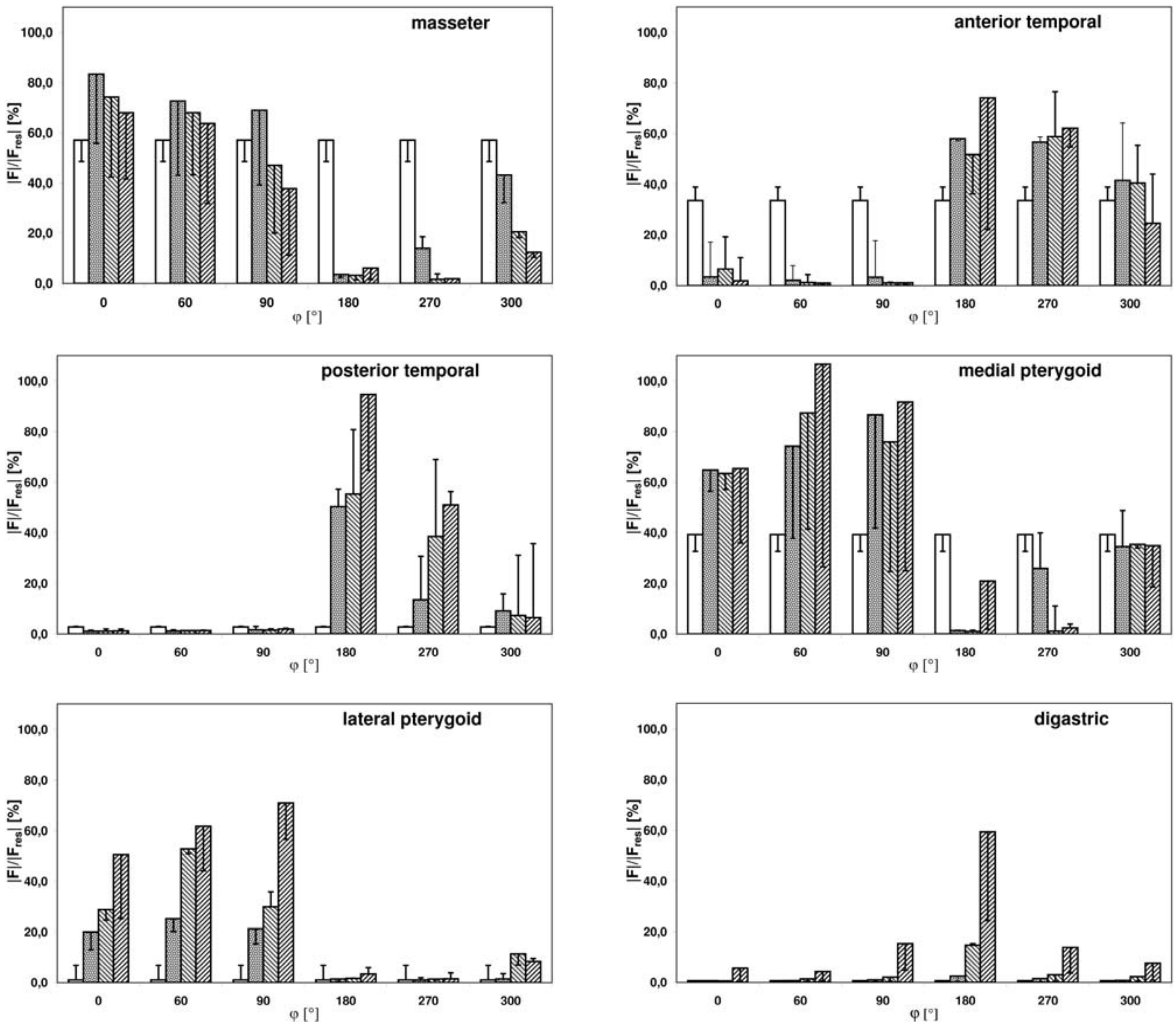


Figure 3: Measured data, and linear and non-linear force law for test person 1 (top) and test person 2 (bottom)

Table 2: Intrinsic muscle stress P [N/mm^2] (t.p.: test person; mv: mean value).
a: θ = 0°; b: θ > 0°, φ = 0°; c: θ > 0°, φ = 180°; d: all tasks

t.p.		**linear**				**non-linear**			
		a	**b**	**c**	**d**	**a**	**b**	**c**	**d**
1	mv	0,19	0,11	0,15	0,15	0,31	0,18	0,59	0,34
	min	0,10	0,08	0,08	0,05	0,24	0,13	0,31	0,12
	max	0,30	0,16	0,25	0,30	0,35	0,24	1,27	1,27
2	mv	0,23	0,12	0,17	0,17	0,49	0,27	0,44	0,42
	min	0,16	0,10	0,11	0,09	0,37	0,18	0,33	0,14
	max	0,35	0,15	0,24	0,35	0,63	0,33	0,53	0,90



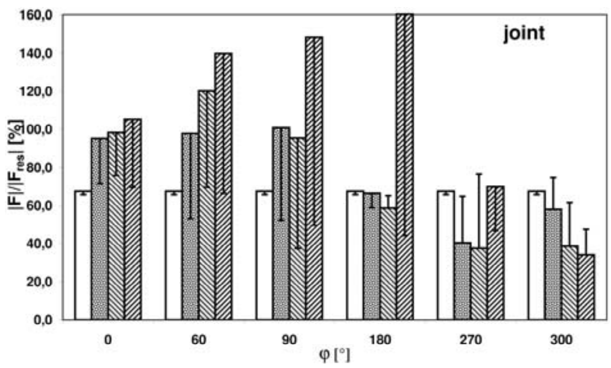


Fig. 4: Muscle and joint forces of the right side for F_{res} = 150 N as a function of angle φ for different values of the cranial angle θ, calculated on the basis of the non-linear force law. Blocks denote the results for test person 1; error bars indicate the difference of test person 2 with respect to test person 1

Table 3: Mean ratio P_{150}/P_{50} over all tasks for the two test persons as quality index for the force law in the interval from F_{res} = 50 N to 150 N

test person	linear force law	non-linear force law
1	1.91	1.81
2	1.32	0.89

Table 4: Direction of joint force in the x,z-plane (angle δ with respect to the x-axis); t.p.: test person

t.p.		φ [°] 0	60	90	180	270	300
		δ [°]					
1	min	252	215	227	243	247	253
	max	283	270	295	303	261	263
2	min	260	248	243	231	269	267
	max	281	266	279	301	293	288

In the following the results for corresponding muscle and joint forces of the right and left side have been averaged. The right muscles and the right condyle perform the same task for $\varphi = 0°, 60°, 90°, 180°, 270°, 300°$ as the left muscles and the left condyle for $\varphi = 0°, 300°, 270°, 180°, 90°, 60°$, respectively. Therefore side effects are eliminated and it suffices to show the results for the 'right' side. These muscle forces along with the joint force are presented in Fig. 4 for both test persons on the basis of the non-linear force law.

Table 3 shows, as a quality measure, the mean of all ratios of P at F_{res} = 150 N and at 50 N for the identical task. If the force law would perfectly describe the real behavior, the ratio $P_{150}/P_{50} = 1$ would be found. It becomes clear that, especially for test person 2, the non-linear force law delivers better results.

Finally, Table 4 displays for both test persons the direction (angle δ) of the joint force in the x,z-plane for all tasks (angle φ). The angle δ is counted from the x- to the z-direction, i.e., in the mathematically positive sense. The values cover the range from $\delta = 215°$ (force in anterior and downward direction) to $\delta = 303°$ (force in posterior and downward direction). $\delta = 270°$ corresponds to a joint force perpendicular to the Frankfort horizontal plane. For nearly all tasks the joint force component in y-direction does not exceed 20% of the total joint force.

Discussion

The values for the muscle volumes calculated from the MRTs, correspond well with those found in literature [2,4]. This holds especially for test persons of about the same age as in this study [4]. This testifies the *in vivo* measurement of the muscle volume with the aid of MRT as a reliable procedure.

Physiological cross-sectional areas and lines of action of the muscle forces are in good accordance with those found in literature [2] and thus confirm these findings. These lines of action were calculated under the assumption of a homogeneous activation of the individual muscles. However, especially for laterally and medially oriented tasks we assume a heterogeneous activation of the musculature as described in [5]. This muscle behavior might essentially influence the lines of action. Therefore, the presented results for the intrinsic muscle stress P are presumably less accurate for these tasks than for the protrusive or vertical (symmetric) tasks. Further studies will address this issue.

The calculated values for the intrinsic muscle stress P in the case of maximum voluntary clenching lie in the range P = (0.30 - 0.43) N/mm^2, and thus correspond well with the value P = 0.37 N/mm^2 given in [2]. The individual analysis, however, shows clearly that, depending on the subject, better results can be achieved with a non-linear than with a linear force law.

With the exception of the anterior temporalis, the individual muscles developed the highest force values in clenching directions which corresponded roughly to their line of action. This supports the assumption that the motor control selects the activation state of the masticatory muscles with regard to their directional effectiveness. The relatively high force generation of the anterior temporalis during lateral and posterior force development, however, might be essential for stabilizing the ipsilateral jaw joint during these tasks.

An unexpected result is (independently of the overall similar activation pattern) the considerable interindividual difference in the amount of the task dependent force generation. As can be seen in Figure 4, the essential difference in force generation between subject 1 and 2 leads to a drastic and highly variable increase of joint loads in subject 1. On the opposite, subject 2 displays a relatively constant joint force during all tasks (ca. 70% of the resultant force). Therefore, it might be speculated that fundamental differences exist between subjects in the amount of muscle force generation (economy of muscle activation) to perform identical motor tasks. This in turn, in the case of high muscle forces, might be a predisposing factor, especially, for overloading the joint structures.

The range of joint forces angles in the sagittal (x,z-) plane amounted to about 90°, nearly symmetrical to the vertical axis. The direction of the reaction forces between 215° and 303° in the saggital plane supports the assumption that the structures in the posterior and anterior superior part of the mandibular fossa are the most loaded tissues during clenching tasks.

Conclusions

Within the limitations of the study we might draw the following conclusions:

1. In vivo measurement of the muscle volume with the aid of MRT is a reliable procedure.
2. The calculation of the intrinsic muscle stress P requires an individual adjustment of the force law (linear vs. non-linear). The presented force and EMG measurements clearly show a non-linear dependence of the muscle on its electrical activity.
3. Motor control seems to favour a directional effectiveness of the muscles when selecting the task-dependent intermuscular activation patterns.
4. Subjects differ in the generation of the amount of muscle force, yet not in the overall activation patterns.
5. Development of high muscle forces might predispose an overloading of the jaw joint tissues.
6. The magnitude of the reaction forces on the condyles rather seems to be an interindividual characteristic than a task-dependent aspect.

Acknowledgements

This investigation was supported by the Deutsche Forschungsgemeinschaft by grants SCHW 307/15-1 and STRU 675/1-1. The authors wish to express their gratitude to Master Precision Mechanic Willi Wendler, Christian Müller and Saskia Käpplein (University of Karlsruhe). Special thanks go to Dr. med. Heinz Schelp for the preparation of the MRTs of the test persons.

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