Alloplastic total temporomandibular joint replacements: do they perform like natural joints? Prospective cohort study with a historical control

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Alloplastic total TMJ replacements: do they perform like natural joints? - Prospective cohort study with a historical control.

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Short Title: **Function of alloplastic total TMJ replacements**

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Abstract

To qualitatively and quantitatively describe the biomechanics of existing total alloplastic reconstructions of temporomandibular joints 15 patients with unilateral or bilateral TMJ total joint replacements and 15 healthy controls were evaluated via dynamic stereometry technology. This non-invasive method combines three-dimensional imaging of subjects' anatomy with jaw tracking. It provides insight into patients' jaw joint movements in real time and their quantitative evaluation. In addition, the patients were evaluated clinically for jaw opening, protrusive and laterotrusive movements, pain, interference with eating, and satisfaction with the joint replacements. Qualitative assessment revealed that compared to unilateral prosthesis, condyles of bilateral total joint replacements displayed similar basic motion patterns. Quantitatively, mandibular movements of artificial joints during opening, protrusion and laterotrusion were all significantly shorter compared to controls. A statistically restricted mandibular range of motion in replaced joints was also observed clinically. 53 % of patients suffered from chronic pain at rest and 67 % reported reduced chewing function. Nonetheless, patients declared a high level of satisfaction with the replacement. This study shows that in order to gain a comprehensive understanding of complex therapeutic measures, a multidisciplinary approach is needed.

Introduction

Temporomandibular joint (TMJ) pathologies, if unresponsive to nonsurgical treatment, may require surgical intervention. For the cases when a TMJ replacement (TJR) is indicated, the discussion is ongoing as to embodiment paradigms. First references to alloplastic TMJ reconstruction attempts date back to the second half of the 19th century when prostheses of different natural materials were implanted immediately after joint excision.[1,2] The development of TMJ reconstructive surgery progressed significantly in 1965 when Christiansen modified his fossa replacement device by adding a condylar element, thus creating the first alloplastic total TJR system.[3] Later on, several other systems brought substantial diversity into the market.[4,5] Alloplastic TJR evolved continuously until the 1980s when fatal consequences of Vitek-Kent (Vitek®; Houston, USA) and Silastic® (Dow Corning; Midland, USA) replacements, such as foreign-body giant cell reaction, bone erosion, persisting pain, alteration in occlusion, mandibular hypomobility, necessitated the removal of numerous prostheses. [6–8] This caused a general mistrust in alloplastic TJR among clinicians and the return to autologous transplantation techniques.[9]

Recently, promising outcomes of new generation alloplastic TJR have been reported. [10–16,] These joint replacements have a better prognosis with respect to reduction of pain level and improvement of jaw function[17]. However, the variety of alloplastic TJR systems shows that none of them has achieved the status of a gold standard. Therefore, the system is chosen according to the surgeon's preferences[5] and their understanding of TMJ function. Despite the considerable literature on long-term results of TJR, there is still little information on biomechanical features of the alloplastic replacements, especially in function. Typically, the functional outcome has been assessed by clinical measurements of interincisal points' range of motion [13,18,19], not providing deeper insight into actual joint kinematics.

The developments in our laboratory in the field of dynamic stereometry allow us to thoroughly assess mandibular kinematics, in particular to track jaw motion and measure the biomechanical environment of the TMJ. Therefore, the goal of this study was to describe mandibular - and especially TMJ – kinematic patterns in patients with existing TJR by means of dynamic stereometry. Secondary objectives were the clinical examination of the jaw range of motion and the assessments of pain level and subjective interference with eating as well as patient perceived satisfaction.

Materials and Methods

For this study, we chose a prospective cohort design with a historical control. Patients' contact data were obtained from clinicians who had performed alloplastic total joint reconstruction between February 2005 and February 2015 in the participating centers. Recruitment lasted between December 2014 and August 2015. Inclusion criteria consisted of: current presence of alloplastic TJR, at least 6 months' time interval since the last surgery and age between 18 and 80 years. Exclusion criteria were: pregnancy, current breast feeding, planned pregnancy during the course of the study, drug or alcohol abuse as well as the inability to follow the procedures of the study, e.g. due to language problems, psychological disorders or dementia. The control group consisted of subjects from a normative database established previously. Inclusion criteria for the control group were the same age frame as well as absence of history and signs or symptoms of temporomandibular disorders (TMD), based on assessments by calibrated examiners according to RDC/TMD[20] and bilateral MR and CT images of TMJs[21]. This study followed the Declaration of Helsinki on medical protocol and ethics and the Ethics Committee of the State of Zurich had given its approval (KEK-ZH-No 2014-0396). Written informed consent was obtained from all participants.

Clinical measurements

Pencil markings were drawn on the lower incisors to define the mandibular mid-line and a conventional dental ruler was used for the assessment of the interincisal point's range of motion and opening pattern. Patients were asked to open maximally (even if experiencing pain), protrude the mandible and eventually shift it to the right and left as far as possible. After performing each movement, patients were given a break of approximately 5 s in order to relax their muscles. All measured values were truncated to the millimeter. Resulting opening patterns were classified into three groups according to the DC-TMD standard protocol: 1) straight: deviation of the mandible ≤ 2 mm from the mid-line; 2) corrected: deviation of the mandible ≥ 2 mm and return to the mid-line before or upon reaching maximum opening; 3) uncorrected: deviation of the mandible ≥ 2 mm from the mid-line.

Assessment of pain and self-perceived function

After clinical measurements, patients were asked about current pain intensity. They rated the pain level according to a Numeric Rating Scale (NRS; 0: "no pain"; 10: "worst imaginable pain")[22–25]. Additionally, patients classified their interference with eating using a similarly constructed Likert scale (0: "ability to chew toughest food, e. g. almonds" 10: "only liquid nutrition"). Finally, the patients' level of satisfaction with the replacement was rated between 0 ("absolutely dissatisfied") and 10 ("completely satisfied").

Dynamic stereometry

The biomechanical characteristics of TJR were assessed by means of dynamic stereometry. This non-invasive method consists in a combination of three-dimensional imaging and jaw tracking and provides an indirect insight into patients' TMJ movements in real time. For the purpose of this study, coronal X-ray image stacks with $0.4 \times 0.4 \times 0.4\ mm^3$ voxels were taken using a digital volume tomography (DVT) scanner (KaVo 3D eXam1, KaVo GmbH, Leutkirch, Germany) with the patient biting into a reference custom-made occlusal splint. The basic technique of dynamic stereometry and its characteristics have been described previously [25].

Experimental procedure

During the first appointment we used a three dimensional scanner (TRIOS; 3Shape, Kopenhagen, Denmark) to acquire digital models of patients' dental arches. Based on the scans, two custom-made splints were custom designed (Rhino 5®; McNeel Inc., Seattle WA, USA; https://www.rhino3d.com) and 3D-printed (Objet Eden 260V™; Stratasys, Eden Prairie MN, USA). At the second appointment splints were rigidly attached to patients' upper and lower frontal teeth using a dental compomer (Twinky Star®; VOCO GmbH, Cuxhaven, Germany) without etching or bonding teeth surfaces. Splints were placed so that they did not interfere with each other or with occlusion in order to avoid any disturbances in performing movements during recording. Patients were instructed to perform the movements of opening and closing the mouth, protrusion and laterotrusion to both right and left. Each movement was recorded 3 times.

Data analysis and statistics

Lateral and medial condylar poles and the mid-point of the main condylar axis (MP) were determined using 3D visualization software for medical images (Amira™ v. 6, FEI, Hillsboro OR, USA). Trajectories of MP were calculated for each motion recording. Vectors were then computed between the resting position (RP, vector origin) and the maximal excursion point (ME, vector tip). X and Y axes were aligned to the sagittal plane with X and Z axes aligned to the Camper plane. X coordinates increased ventrally, Y cranially and Z to the patient's right side. When comparing vector components, right joints were mirrored, so that the Z component always increased in medial direction.

Statistical analysis was performed using IBM SPSS® Statistics version 23 software. Mann-Whitney tests were applied to the averages of the repetitions to determine the differences for each variable between the study groups. The level of significance was set at $\alpha=0.05$.

Results

Contact data of 30 patients was collected from participating centers. Fifteen of these patients eventually participated in the study. Figure 1 shows the recruitment flow. Reported indications for TJR surgery were: severe degenerative joint disease with compromised TMJ function, failed primary therapy after TMJ trauma, TMJ ankylosis, condylar resorption, pigmented villonodular TMJ synovitis or mandibular keratocyst extending to the TMJ. TMJ prostheses used were from different manufacturers (Rotec®, Weisendorf, Germany; TMJ Concepts, Inc., Ventura, CA, USA; Biomet®, Jacksonville, FL, USA). The control group consisted of 15 healthy subjects. Table 1 presents demographic and baseline characteristics of both groups. In the patients group, the mean age was 52 years (range 24 to 72), in the control group 28 years (range 24 to 56). The mean age at time of surgery - was 47 years (range 21 to 66), and the mean time from operation to study examination was 4.8 years (range 0.7 to 9.2).

The results of clinical examination are presented in Table 2. For bilaterally operated patients the lateral excursion movement was averaged for left and right excursion.

Figure 2 shows typical opening/closing paths (incisal points and mid-points of the main condylar axes) for controls (a, b) as well as for patients with unilateral (c, d) and bilateral (e, f) joint replacements. A vector between the resting position (RP) and the maximal excursion point (ME) is shown in Figure 3 as an example.

Table 3 presents the vector lengths and vector component values for opening and protrusion and Table 4 for laterotrusion. Alloplastic condyles behaved similarly (concerning vector length and its components) no matter if the patients had been operated uni- or bilaterally. A significant difference was found in vector length for protrusion ($p=0.04$) and for ipsilateral laterotrusion ($p=0.026$).

Vector lengths for opening, protrusion and contralateral laterotrusion were significantly shorter in artificial than in natural joints ($p=0.01$, <0.001, <0.001 respectively). The vector component X was significantly different for protrusion ($p<0.001$) and contralateral excursion ($p<0.001$), Y for opening ($p=0.001$), protrusion ($p<0.001$) and contralateral excursion ($p<0.001$), Z for ipsilateral excursion ($p=0.026$). One subject could not perform the laterotrusive movements due to intense pain. Therefore, the statistics was calculated considering a missing value.

When comparing the natural joints in unilaterally operated patients with the controls, the vector component X pointed significantly more ventrally for opening ($p=0.021$), Y and Z pointed significantly more cranially resp. more medially for ipsilateral laterotrusion ($p=0.047$

and p=0.021) and *Y* more cranially for contralateral laterotrusion (p=0.007). Figure 4 shows the average vectors between RP and ME of the mid-point of the main condylar axis for opening/closing (a), protrusion (b) and contralateral laterotrusion (c) in the natural joints of unilaterally operated patients as well of controls.

There were two cases of incidental findings when performing data acquisition and analysis. One unilaterally operated patient showed signs of ankylosis of the remaining natural joint on the contralateral side, which was confirmed by DVT and MRI. However, the patient refused to undergo surgical revision and remains under physician's observation. The second incidental finding was an inflammation of soft and hard tissues surrounding the joint replacement, resulting in high pain intensity and limited function. The patient underwent a revision operation. Both patients with incidental findings were included in the study because the incidental findings did not lead to exclusion according to our criteria.

Discussion

Despite acceptable mandibular function, patients with total alloplastic TJR seldom reach norm jaw opening values[13,16,27]. The objective of this study was to assess the mobility of natural and alloplastic condyles in patients with existing TJR. Mandibular kinematics was analyzed by means of dynamic stereometry. Artificial condyles had similar basic motion patterns in unilateral and bilateral surgeries, although protrusive and laterotrusive movements were more reduced in case of bilateral replacement. Generally, except for ipsilateral laterotrusions, surgery resulted in shorter condylar excursions for artificial joints than for controls, which was reflected in a significant reduction of dorsoventral components for protrusion and contralateral laterotrusion. However, also the motion of natural joints differed between unilaterally operated patients and controls: during opening, condylar excursions in patients were almost twice as large in ventral direction as in controls; during ipsilateral laterotrusions, condyles of patients moved significantly cranially and medially, whereas condyles of controls moved significantly caudally and laterally; finally, in contralateral laterotrusions, natural joints of patients moved significantly less caudally than in controls.

To our knowledge, this is the first study that performed an accurate quantitative functional analysis of alloplastic total TMJ replacements by means of dynamic stereometry, which provides an overall virtual representation of mandibular anatomy in motion. Conversely, other studies tracked only the interincisal point (IP), giving no insight into TMJ kinematics25. Here, no difference between patients and controls for opening and protrusive movements was found. However, the lack of differences in jaw gape between patients with unilateral TJR and controls might be misleading. Indeed, deviations in IP motion patterns, caused by abnormal joint mobility can occur without affecting the maximal interincisal opening (MIO). Our results show that, for jaw opening, the patients' natural joints moved significantly more ventrally than in controls, thus pulling the whole mandible forward, still dissembling a normal IP range of motion. For protrusions, the natural condyles of patients shift similarly to those of controls, thus causing an acceptable IP translation. Finally, both studies agreed in finding significant differences between unilaterally operated patients and controls for contralateral laterotrusions, in which prosthetic joints cannot be pulled forwards.

There are several possible reasons for the limited function of TJR discussed in the literature. These are the lack of lateral pterygoid muscle function and hypotrophy of other masticatory muscles[28], excessive scaring tissue resulting from multiple previous operations[12,29] and the form of the replacement itself[30]. Using a mandibular motion simulator it has been observed that also in cases where the opening range of motion is not limited by the replacement, the laterotrusion and protrusion were vastly impaired[30]. Authors suggested that even if the lateral pterygoid was reattached and did not lose its function, the current design of the prosthesis makes the achievement of a normal mandibular motion impossible.

Linsen et al. investigated condylar range of motion (CRoM) for jaw opening, and incisor range of motion (InRoM) for opening, protrusion and laterotrusion in 17 patients with alloplastic TJR using an ultrasound-based jaw tracking system. At a minimum of 12 months postoperatively, the linear distance for CRoM was 14.05±4.14 mm in patients operated with the indication of condylar hypomobility and 17.49±5.68 mm in the group of patients with a history of condylar instability. The curvilinear path of the incisal point for the laterotrusion was 1.00 mm and 1.10 mm respectively and the linear distance for protrusion was 1.94 mm and 3.10 mm. However, when allocating the patients to indication-based groups the authors did not consider if patients were operated uni- or bilaterally, thus neglecting the influence of remaining natural joint in the unilaterally operated ones. The condylar hypomobility group consisted of mainly bilaterally operated patients (7 out of 8), contrarily to the condylar instability group, which consisted of mainly unilaterally operated patients (6 out of 9). In our clinical examination, bilaterally operated patients showed notably lower range of motion for both latero- and protrusion when compared to unilaterally operated group, which is consistent with the findings of the discussed study.

The results of the control group are consistent with findings of other authors who investigated the condylar range of motion in healthy population. One study measured the linear distance of condylar path in 21 adult females with the results of 12.8 ± 2.8 mm (range 8.1–19.2 mm)[31] whereas another one tracked the movement of the terminal hinge axis in 27 adult females resulting in 11.9 mm distance[32]. According to DC-TMD diagnostic criteria, MIO smaller than 40 mm is considered to be limited. Okeson reports that only 1.2 % of young adults opens less than 40 mm. Other authors defined a normal incisal range of motion as 38-50 mm for opening, 7-10 mm for laterotrusion and 8-12 mm for protrusion[30]. In our work all clinical values for both uni- and bilaterally operated patients remained under the suggested normal range. Nonetheless, our clinical outcomes are consistent with results of other authors and in the range suggested as acceptable by Giannakopoulos et al [16]. Mercuri et al. reported mean MIO of 32.7 $\pm$ 5.5 mm after 5 years follow-up [13], starting with 31.6 mm 1 year postoperatively and stating 31.3 mm 13 years later. Wolford et al. [10] in their twenty-years follow-up study reported mean MIO to be 36.2 $\pm$ 7.8 mm after the full follow-up period. In another follow-up study on 256 patients, the group mean MIO was 29.5 $\pm$ 6.55 mm after 3-year follow-up[16].

A substantial part of TJR patients suffers from persisting pain and limited chewing function long after surgical treatment and healing processes are completed. In the already mentioned study in a group of 256 patients[16], pain intensity, interference with eating, and treatment satisfaction were assessed by means of visual analogue scales three years postoperatively. The results are similar to ours regarding all three objectives. In our study, only one patient reported low satisfaction with the therapy. In this case, dissatisfaction was reported despite an acceptable MIO value of 30 mm and low pain intensity at rest (VAS of 2). The factor that was of deciding importance was the impairment in diet, since the patient was able to consume only liquids since chewing caused intense pain. It is worthwhile noting that, despite relatively low values of current pain intensity, half of the examined TJR patients suffered from chronic pain at rest and two thirds had a certain level of chewing function impairment. It has been observed -in both orthopedic and TMJ studies- that the pre-operative pain, number of previous TMJ operations as well as comorbidities greatly influence the post-operative outcomes[13,33,34]. Thus it is of major importance to discuss this issue with the patient before performing any irreversible interventions. Patients need to be aware, that the relief of pain is not the primary goal of the operation, can only be considered as of secondary benefit and is not guaranteed. Only by fully addressing this question the potential misunderstandings or disappointments can be avoided.

On one hand the rarity of the investigated intervention in Swiss population and on the other hand the lacking interest of patients resulted in a small number of participants, which is a study limitation. According to international guidelines, irreversible therapy for TMJ pathologies are rarely indicated, since conservative measures that also address psychosocial burdens are widely successful[35]. Moreover, several patients refrained from participation in the study, either because of poor general condition, advanced age and dependence on third persons, or on the contrary, due to young age and high social and professional obligations. A continuous relationship with the surgeon was of major importance for patients to be willing to participate in the study. For this reason, some results may be slightly biased, such as patients' satisfaction. Furthermore, due to the small number of cases, weak gender matching could be a study limitation. Conversely, lack of age matching between patients and controls is considered to have a scarce influence on the results, due to the large variation of jaw opening values within any age range in healthy populations[26].

In order to gain a comprehensive understanding of TJR therapy, as a particularly complex treatment measure, it is recommendable to conduct studies not only with a larger sample size than the one investigated in this study, but also to put an emphasis on a multidisciplinary approach. This will provide an evaluation of the procedure from various points of view, ranging from mathematical modelling, through histological observations, to the interdisciplinary clinical assessment of function and psychosocial factors.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at (doi)

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The authors certify that the research described in the manuscript is original, not presently under consideration for publications elsewhere, and free of conflict of interest.

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Tables

Table 1: Demographic and baseline characteristics

Variables	Unilateral (n=7)	Bilateral (n=8)	Controls (n=15)
Gender			
Males*	1 (14.3 %)	3(37.5 %)	9 (60.0%)
Females*	6 (85.7 %)	5(62.5 %)	6 (40.0%)
Age (years)#	55.1 (43.1; 69.7)	44.6 (37.0; 65.7)	26.1 (25.2; 28.8)
Time from operation to examination (years)#	4.4 (3.8; 7.8)	4.4 (1.3; 5.4)	N/A
Numeric rating scale for pain#	3.0 (0.0; 5.0)	1.0 (0.0; 2.8)	N/A
Interference with eating#	3.0 (2.0; 4.0)	3.0 (1.5; 7.7)	N/A
Level of satisfaction with replacement#	8.0 (7.0; 10.0)	8.5 (6.5; 9.8)	N/A

N/A: not applicable
Data are presented as:
* amount and percentage
#median (p25; p75)
Numeric Rating Scale for pain ranges from 0 (no pain) to 10 (greatest imaginable pain).
Interference with eating scale ranges from 0 (ability to chew hardest possible food, e. g. almonds) to 10 (only liquid nutrition).
Level of satisfaction with replacement ranges from 0 (absolutely dissatisfied) to 10 (completely satisfied).

Table 2: Clinical measurements

Variables	Unilateral (n=7)	Bilateral (n=8)
Opening Pattern*		
Straight	0	7 (87.5 %)
Corrected	2 (28.6 %)	0
Uncorrected	5 (71.4 %)	1 (12.5 %)
Maximum Unassisted Opening (mm)#	39.0 (32.0; 55.0)	34.0 (30.0; 40.25)
Lateral excursion of the replaced joint (mm)#	2.0 (0.5; 4.0)	1.5 (1.13; 2.63)
Lateral excursion of the natural joint (mm)#	7.0 (2.0; 11.0)	N/A
Protrusion (mm)#	2.0 (0.0; 5.0)	0.0 (0.0; 0.0)

N/A: not applicable
Data are presented as:
*amount and percentage
#median (p25; p75)

Table 3: Vector components and vector lengths for opening and protrusion movements

Variables	Unilateral (n=7)		Bilateral (n=8)	Controls (n=15)
	Natural side	Operated side	Both sides	
Opening movement				
X	14.39±9.46§ (10.89; 7.09; 25.85)	5.18±3.38 (4.84;2.7; 7.38)	3.79±1.86 (3.26; 2.3; 5.75)	6.14±3.32§ (5.64; 4.07; 8.4)
Y	-5.69±3.1 (-6.49; -8.18; -3.08)	-3.98±2.53 (-3.57; -5.82; -1.38)	-1.69±2.51 (-2.64; -3.92; 1.26)	-6.33±2.31 (-6.11; -7.79; -5.15)
Z	0.42±1.65 (0.26; -0.89; -1.15)	-0.26±1.24 (0.17;-1.09; 0.72)	-0.02±0.03 (-0.01; -0.04; 0.0)	0.02±0.09 (0.04; 0.0; 0.08)
L	15.87±9.38 (12.67; 12,67; 26.66)	7.12±3.21 (6.0; 4.63; 10.09)	4.74±2.04 (4.84; 3.09; 6.58)	9.01±3.8 (8.3; 7.19; 12;43)
Protrusion movement				
X	7.3±6.01 (6.82; 0.32; 11.77)	1.15±2.21 (0.36; -0.93; 2.68)	0.48±0.38 (0.5; 0.09; 0.83)	5.4±1.13 (5.19; 4.85; 6.43)
Y	-3.31±2.58 (-3.03; -5.68; -0.31)	0.2±1.2 (-0.06; -0.94; 1.22)	0.24±0.45 (0.11; -0.07; 0.5)	-5.33±1.24 (-5.64; -6.32; -4.63)
Z	0.16±1.15 (-0.03; -0.46; 0.96)	-0.18±0.96 (-0.14;-0. 71; 0.26)	-0.15±0.28 (-0.04; -0.17; 0.1)	0.0±0.04 (-0.01; 0.01; 0.02)
L	8.3±6.29 (8.57; 1.0; 13.48)	2.36±1.64* (2.09; 1.03; 2.92)	0.95±0.57* (0.93; 0.56; 1.51)	7.72±1.26 (7.58; 6.87; 8.86)

Data are presented as mean ± standard deviation (median; p25; p75)
X, Y, Z: Cartesian vector components
L : Vector length
§significant difference between patients and control
*significant difference between unilateral and bilateral replacement

Table 4: Vector components and vector lengths for left and right laterotrusion movements

Variables	Unilateral (n=7)				Bilateral (n=7)		Controls (n=15)	
	Natural side		Operated side		Both sides			
	Ipsilateral	Contralateral	Ipsilateral	Contralateral	Ipsilateral	Contralateral	Ipsilateral	Contralateral
X	-0.31±1.0 (-0.13; -0.91; 0. 23)	6.74±6.28 (6.66; 1.17; 11.36)	1.11±1.8 (0.64; -0.06; 1.97)	0.19±0.53 (0.12; -0.16; 0.79)	-0.72±0.34 (-0.05; -0.29; 0.05)	0.56±0.91 (0.56; 0.29; 0.97)	0.37±0.31 (0.43; 0.9; 0.57)	5.94±2.16 (6.25; 4.66; 7.64)
Y	0.35±0.89§ (0.07; -0.29; 1.6)	-2.83±2.41§ (-3.06; -4.64; -0.32)	0.12±1.74 (-0.38; -1.05; 0.16)	0.21±1.08 (-0.11; -0.33; 0.8)	0.04±0.19 (0.16; -0.19; 0.18)	-0.32±0.49 (-0.16; -0.53; -0.08)	-0.43±0.48§ (-0.36; -0.74; -0.03)	-5.83±1.86§ (-6.46; -6.9; -5.61)
Z	0.34±1.22§ (0.2; -0.11; 0.59)	0.56±0.98 (0.05; 0.0; 0.95)	-0.71±1.06 (-0.08; -1.82; 0.05)	1.03±1.06 (0.78; 0.25; 1.82)	-0.7±0.26 (-0.68; -0.82; -0.41)	0.74±0.22 (0.7; 0.64; 0.84)	-0.68±0.67§ (-0.7; -0.99; -0.18)	1.02±0.75 (1.09; 0.48; 1.46)
L	1.77±1.01 (1.87; 0.86; 2.94)	8.0±6.33 (7.6; 1.25; 13.18)	2.52±1.69* (2.26; 1.33; 4.28)	1.66±1.04 (1.38; 0.89; 2.83)	1.06±0.2* (1.11; 0.84; 1.22)	1.38±0.56 (1.19; 1.02; 1.95)	1.35±0.66 (1.28; 0.89; 1.8)	7.91±1.49 (8.01; 6.88; 9.06)

Data are presented as mean ± standard deviation (median; p25; p75)

X, Y, Z: Cartesian vector components

L : Vector length

§significant difference between patients and control

*significant difference between unilateral and bilateral replacement

Captions to illustrations

Figure 1

Recruitment flow chart.

Figure 2

Side (left) and frontal view (right) of typical opening/closing paths of incisal points and mid-point of the main condylar axis (red lines) for controls (a, b), unilateral TJR patients (c, d) and bilateral TJR patients (e, f).

Figure 3

Graphical representation of the vector (blue arrow) calculated between the resting position (RP) and the maximal excursion point (ME) for an opening/closing movement of the mid-point of the main condylar axis, displayed here with a red line.

Figure 4

Geometrical representation of the vectors between RP and ME of the mid-points of the main condylar axes for opening/closing (a), protrusion (b), and contralateral laterotrusion (c) in the natural joints of unilaterally operated patients (red cone) and of controls (green cone). The cone height represents the group median of the vector length, whereas the radius of the cone base is the standard deviation.