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Test-retest and accuracy of measuring the position and orientation of the human mandible via magnetic sensors: a pilot study

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***Abstract*—Obstructive sleep apnea is a common type of sleep-disordered breathing, often treated with an oral appliance that protrudes the mandible. This therapy widens the upper airway thereby eliminating and/or preventing collapses and/or obstructions of the upper airway during sleep. Up till now, monitoring of the actual position of the mandible during therapy was not available – although this should be considered a prerequisite in the process of judging treatment efficacy – thus impeding therapy compliance monitoring. To optimize therapy, patient-based data need to be collected during the device's use. At present, electronic sensors attached to the oral appliance monitoring the temperature in the oral cavity are used to objectify therapy compliance as a simple time-logged binary signal: wearing-not wearing. The current paper presents an in-vitro set-up for monitoring both position and protrusion of the mandible relative to the upper jaw. Two magnetic sensors are attached to the upper maxillary part of an oral appliance in combination with two magnets affixed to the lower mandible part of the oral appliance. The mandibular position relative to the maxilla was measured with an accuracy of 0.5 mm for a range of 17.5 mm in the protruding direction.**

Keywords— Obstructive sleep apnea; oral appliance; Hall sensors

I. INTRODUCTION

Obstructive sleep apnea (OSA) is a common type of sleep-disordered breathing affecting 24% of men and 9% of women in the age group of 30 to 60 [1]. A possible treatment is the use of an oral appliance (OA_m) that protrudes the mandible during sleep [2]. Such an intraoral appliance brings the mandible forward, thereby preventing the upper airway from collapsing and providing an uninhibited airflow, and hence precluding sleep-disordered breathing and many of its unwanted night- and even daytime effects [5].

Knowledge of the patients' individual compliance towards the treatment and a real time assessment of the therapy are absolute prerequisites for the improvement of the overall therapeutic effectiveness and efficacy of an OA_m [4]. Equipping the OA_m with a temperature sensor already allows for the registration of the time that the OA_m is actually being worn, thereby revealing treatment compliance [5-8]. However, little is known about the relative position of the jaws during the treatment. Since most OA_m need additional forward titration by the patient in search for the optimal therapeutic position, quantitative knowledge of such adjustments as well as the continuous and instantaneous positioning of the mandible can be considered crucial to the follow-up and the optimization of the treatment [9]. Magnetic fields are suited to derive relative positions [10] that can be mapped by the Hall effect.

It is the aim of the present paper to provide an in-vitro set-up using magnets and magnetic Hall sensors in an OA_m that allow for the measurement of the mandibular protrusion relative to the maxilla.

II. METHODS

A. Jaw movement parameters

In order for the sensors to be able to detect clinically relevant distances, the following requirements were defined, derived from existing anthropometrical data on the range of mandibular motion [11] and previous studies on efficacy of OA_m therapy in terms of maximal protrusion [12]:

- minimum range of the protrusion distance of 20 mm with an accuracy of 0.5 mm,
- minimum range of the lateral distance of 10 mm (both left and right) with an accuracy of 0.5 mm,
- minimum range of the opening distance of 20 mm (between the maxillary and mandibular central incisors) with an accuracy of 0.5 mm.

B. *Articulator*

Lower jaw movements relative to the maxilla can be simulated using a semi-adjustable non-condylar articulator (Artex®, Amann Girbach AG, Koblach, Austrai, [13], Fig. 1) that is used to reproduce the actual movements of the patients' mandible but in the dental lab. Gypsum casts of maxillary and mandibular teeth arcs were fixed in articulator using averaged position parameters. Protruding the mandible was mimicked by retruding the maxilla for this type of articulator. The articulator was further equipped with adjustment screws that allow for controlled protrusion and/or opening movements. The vertical distance between the frontal central incisors was used as a measure for the amount of opening. The lateral movement was simulated by moving the maxilla from right to left relative to the mandible. Although more complex physical models of the temporomandibular joint exists [14], the selected articulator is a commonly used device to simulate in-vivo actuations of the mandible, in the present case for the purpose of simulation of titration of the OA_m, because it is recommended to keep the opening constant thereby allowing the OA_m to effectuate only horizontal displacements of the mandible [12].

C. *Oral appliance*

Using vacuum-forming techniques, an approximately 2 mm thick layer of plastic [Erkodent, Erkoflex, Germany] was custom-made and applied to both upper and lower jaw casts. Thus, the OA_m was tailored to this specific in-vitro model in order to simulate in-vivo conditions. The sensors and the magnets were affixed to this layer of plastic as shown in Fig. 1. A schematic overview of the magnets and sensors is shown in Fig 2.

D. *Sensors and magnets*

The selected sensors are capable of sensing the strength of a magnetic field in two dimensions [15]. The MLX90333 (SOIC8) is a monolithic sensor featuring the Triaxis® Hall technology: sensitive to the 3 components of the flux density applied to the surface of the sensor (BX, BY and BZ) with a resolution of 50 to 75 mT. To obtain a three-dimensional measurement, a second identical sensor was used. Once the magnets were attached to the OA_m, the relative position of the sensors was determined by placing them directly above the magnets, enabling them to sense the magnetic field at the largest range in distance between the sensor and the magnet.

The magnets on both right and left sides are placed such that the poles are facing up and downwards according to manufacturer's instructions [15]. The size of the cylindrical magnets is 5.0 mm in diameter and 2.0 mm in height, such that the magnets could be implemented in an in-vivo setting, taking into account the OA_m dimensions.

The surface of the right sensor is placed horizontally and is used for sensing the protrusion and lateral position of the mandible relative to the maxilla. The surface of the left sensor is placed vertically, and is used for sensing the opening of the mouth. These orientations were again selected to get the best reading of the sensors in accordance with the manufacturer's instructions [15].

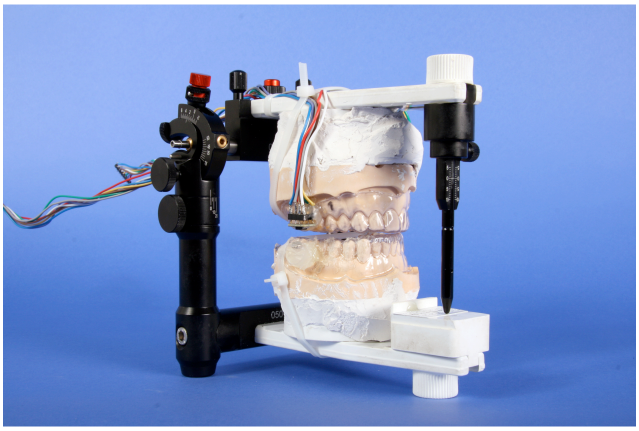

Fig. 1. Test setup articulator.

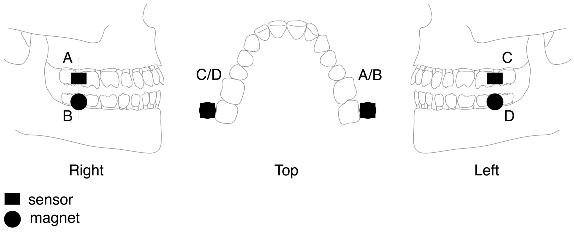

Fig. 2. Placement of sensors (orientation not displayed) and magnets. A: right side sensor, B: right side magnet, C: left side sensor, D: right side magnet.

For the right sensor the vertical distance between the sensor surface and surface of the magnet was 5.30 mm ± 0.04 mm and the vertical distance between the top surface of the left magnet and the center of the left sensor was 9.27 mm ± 0.06 mm for the left sensor. These measurements were taken with an analog caliper when the protrusion was set at 4.5 mm and the setscrew for opening was set to 0.0 mm. By doing, so the right and left sensor are placed directly above the corresponding magnet. As the shortest sensor-magnet distance at the left side is much larger than at the right side, and increases more with the opening of the mandible than protruding the mandible, two magnets are used at the left side, whereas one magnet is used at the right side. Strength is an easily- measured parameter that relates to the force of the magnetic field, and thus also to the performance of the Hall sensor. The strength of the magnets was tested using a force gauge [Hunterspring LKG-5, Ametek, USA]. The gauge was attached to a block of wood by a metal hook. The magnet was glued to the wooden block and placed on a solid steel block before pulling the magnet of the plate by the force gauge. This sequence was repeated 10 times with both one and two magnets. With just one magnet, a holding force of 3.87N ± 0.15 N was measured. By using two magnets at the same time in superposition a holding force of 5.53 N ± 0.25 N was measured.

E. *Connecting the sensors*

The test set-up required the reading of the analog signal created by the sensors when exposed to a magnetic field of sufficient strength. This signal was uploaded to a computer using an Arduino Uno microcontroller [16] and processed by using Arduino software. The ports of the sensor were connected to the Arduino board in a SOIC8 package (14), with the use of a Prototype Shield v3 [Flamingo EDA, China].

The analog signal was read out to a PC by connecting the Arduino Uno using an USB-cable and connecting this to a USB-type 2.0 port.

F. *Test sequence*

To assess validity and accuracy of the monitoring system, movements were manually simulated with the articulator by changing the position of the maxilla, while the analog data of the sensors were monitored. The following movements were performed:

1. opening movement with a retruded position of the mandible relative to the maxilla of -1.5 mm and protrusions of 0.0 mm, 2.0 mm and 4.5 mm;
2. lateral movement (both left and right) with an opening of 0.0 mm and a retrusion of the mandible relative to the maxilla of -1.5 mm and protrusions of 0.0 mm, 2.0 mm and 4.5 mm;
3. from maximal retrusion to maximal protrusion of the mandible with an opening of the mouth measured by the distance between the magnet and the sensor of: 0.0 mm, 1.0 mm, 2.0 mm, 3.0 mm, 4.0 mm, 5.0 mm, 6.0 mm and 7.0 mm.

Each movement was done in steps of 0.5 mm measured by an analog caliper. For each 0.5 mm step in all the tested movements, the data for each sensor was recorded at an initial sample rate of 10.000 samples per 0.4734 milliseconds, which then were averaged over the recorded timeframe.

Measuring the maximal protrusion of the mandible was done by retruding the maxilla to the most dorsal position within the physical constraints of the articulator and then protruding to the most ventral position in steps of 0.5 mm.

Every output signal was assessed twice both to average the data and to get an insight in the data changes and instant stability. In addition, the protruding movement with an opening of 0.0mm was performed nine times and for each analog input the average value and standard deviation was calculated as an accuracy measure under test-retest conditions.

III. RESULTS

A. *Sensor values test-retest*

Table 1 shows the analog output as measured by the Arduino system of the two sensors for each step of the test sequence of protruding the mandible forward relative to the maxilla with an opening distance of 0.0 mm. The first column shows the protrusion distance, which was first fixed by the setscrews of the articulator at a distance of 4.5 mm stated on the articulator. From there the traveled distance was measured by the horizontal movement of the pin used to set the opening of the mouth, which moves on a flat horizontal surface as seen in Fig. 1. The inter-incisal opening was kept constant at 0.0 mm as measured by the opening setscrew. The remaining columns show the collected data in which A1 and A2 represent the analog data of the magnetic strength measured by the left sensor. A3 and A4 represent the analog data of the magnetic strength measured by the right sensor. The data with a minimum value of 0 and a maximum value 1024 represent the voltage the sensors let through. This voltage has a minimum of 0 V and a maximum of 5 V. This conversion is performed by an analog-to-digital converter on the Arduino Uno board.

Note that, as a spillover, the method to attach position sensors to an Artex and measure outcome as a function of displacement, can be used to calibrate the position sensors. In particular, the resulting data calibrate the Hall position sensors with respect to the magnets used in this particular test setting.

The analogue output signals that are sufficiently accurate under test-retest conditions to determine protruded distance with an accuracy of at least 0.5 mm are highlighted in Table 1. The resulting analogue signals as a function of protrusions are displayed in Fig. 3 with accuracy discplayed by the thickness of the graphs. This yields a measurable range of 17.5 mm with an accuracy of at least 0.5 mm under test-retest conditions.

B. *Range*

The maximum range of the sensor was measured by adjusting the protrusion, lateral movement or opening to the minimum and maximum distance within the physical constraints of the articulator and in which the sensors could still detect a magnetic field and therefore produce a read-out signal.

Table 2 shows that the maximum protrusion range is 17.5 mm, at an opening of 0.0 mm, which comes close to the desired 20 mm. At a vertical opening of 7.0 mm no more data could be read out by either sensor.

Table 3 shows that the maximum vertical opening range was 7.0 mm at a protrusion distance of 0.0 mm, which is far from the desired range of 20 mm.

Table 4 shows that the performed lateral movements resulted in a maximum range of 12.0 mm to the right side at a fixed protrusion of 0.0 mm. The maximum measurable distance when moving the mandible to the left was 9.5 mm. This resulted in a combined lateral range of 21.5 mm, which meets the requested range of 10 mm to the left and right side.

C. *Accuracy*

Analogue data was screened for consistency and those ranges that yield constant output were retained. Measurable range of protruding movement at 0.0 mm is 17.5mm covering 35 steps of 0.5 mm. The average interval in the measured data per measuring point was 21.50 ± 11.72, illustrating that most measured data distinguish an individual step, especially when combined with other read-out signals. Similar quantities are found for other movements, although these were only based on two performances.

TABLE I. – AVERAGE ANALOG SENSOR VALUES AND STANDARD DEVIATION FOR PROTRUSION MOVEMENT WITH AN OPENING OF 0.0 MM

Protrude distance (mm)	Average data value per analog input			
	A1 ± SD	A2	A3	A4
18,0	10±7	10±7	5±3	5±3
17,5	10±7	10±7	6±4	6±4
17,0	10±7	10±7	6±4	6±4
16,5	11±7	11±7	6±4	6±4
16,0	11±7	11±7	6±4	6±4
15,5	13±10	13±10	272±394	153±218
15,0	12±8	12±8	921±4	508±7
14,5	13±9	13±9	921±4	507±6
14,0	13±10	13±10	918±5	503±7
13,5	13±10	13±10	913±5	500±5
13,0	13±10	13±10	905±4	498±6
12,5	14±11	14+11	890±6	494±4
12,0	16±17	16±17	877±6	494±4
11,5	83±97	103±125	859±9	491±7
11,0	186±137	217±160	840±7	490±5
10,5	287±86	310±94	818±12	489±6
10,0	334±7	337±12	802±7	490±5
9,5	349±7	327±12	784±7	490±5
9,0	370±8	322±11	767±5	493±7
8,5	393±9	321±11	746±7	494±6
8,0	415±6	296±10	721±8	495±6
7,5	431±6	279±13	694±9	493±6
7,0	449±6	259±13	662±10	490±8
6,5	467±6	237±11	633±5	479±9
6,0	484±7	212±14	631±14	473±7
5,5	501±6	184±17	641±5	485±7
5,0	517±7	162±15	611±16	495±9
4,5	530±8	145±16	575±19	500±7
4,0	548±7	137±13	543±9	504±8
3,5	556±10	132±13	513±8	509±8
3,0	551±7	132±14	482±7	514±9
2,5	563±6	137±15	457±8	517±8
2,0	578±5	148±15	432±9	523±9
1,5	595±5	164±16	412±6	525±10
1,0	611±6	192±21	387±5	531±10
0,5	633±7	229±18	362±7	537±8
0,0	650±9	241±10	341±8	543±10
-0,5	676±9	260±16	312±6	552±8
-1,0	699±8	294±8	288±7	558±11
-1,5	709±7	301±20	251±17	560±9
-2,0	725±9	351±21	209±17	554±6
-2,5	744±9	368±9	169±14	558±6

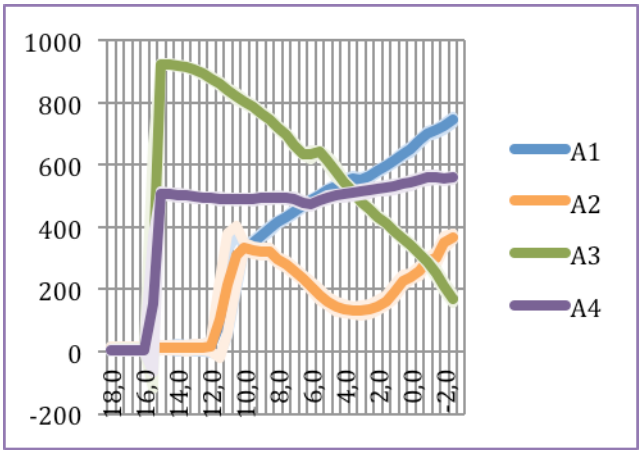

Fig. 3. Analogue sensor signals and accuracy as a function of protruded distance at 0.0 mm opening.

TABLE II. MEASURED SENSOR RANGE IN PROTRUSION AT VARIOUS OPENING POSITIONS

Protrusion	
Opening	Range measured
0.0 mm	17.5 mm (+15.0 mm ↔ -2.5 mm)
1.0 mm	17.5 mm (+15.5 mm ↔ -2.0 mm)
2.0 mm	17.5 mm (+15.5 mm ↔ -2.0 mm)
3.0 mm	17.0 mm (+14.5 mm ↔ -2.5 mm)
4.0 mm	14.5 mm (+12.0 mm ↔ -2.5 mm)
5.0 mm	13.0 mm (+9.5 mm↔ -2.5 mm)
6.0 mm	9.0 mm (+10.5 mm ↔ +4.0 mm & 0.0 mm ↔ -2.5 mm)
7.0 mm	(No usable data read out)

TABLE III. MEASURED SENSOR RANGE IN OPENING AT A FIXED PROTRUDED DISTANCE

Opening	
Protrusion	Range
+4.5 mm	5.5 mm (10.8 mm ↔ 5.3 mm)
+2.0 mm	6.5 mm (11.8 mm ↔ 5.3 mm)
+0.0 mm	7.0 mm (12.3 mm ↔ 5.3 mm)
-1.5 mm	3.5 mm (6.6 mm ↔10.1 mm)

TABLE IV. MEASURED RANGE LATERAL MOVEMENT AT A FIXED PROTRUDED DISTANCE AND AN OPENING OF 0.0 MM

Lateral movement	
Protrusion	Range
-1.5 mm	20.0 mm (8.5 mm← 0 → 11.5 mm)
0.0 mm	21.5 mm (9.5 mm← 0 → 12.0 mm)
2.0 mm	20.5 mm (9.5 mm← 0 → 11.0 mm)
4.5 mm	20.5 mm (9.5 mm← 0 → 11.0 mm)

IV. DISCUSSION

The present study shows that the position of the mandible can be effectively monitored using two magnetic sensors, capable of detecting changes in a magnetic field in two dimensions. This was accomplished within a range of 17.5 mm in protrusion, 7.0 mm in opening and 21.5 mm in lateral-to-lateral movements.

In the present set-up, the accuracy with a precision of 0.5 mm is presently achieved for a protrusion with a vertical opening of 0.0 mm. The ranges wherein the sensors detected the actual protruded distance and opening movements of the mandible are not yet the required maximal ranges. These limitations could be overcome by selecting more sensitive sensors, optimize sensor-magnet configuration and/or stronger magnets and will need to be studied further. Indeed, a superposition of two magnets used in the present setting already results in a 143% increase in holding force which might induce similar effects on sensor range and accuracy.

Nevertheless, the applied technology could enable not only the monitoring of the compliance of patients with OA_m treatment but also evaluate the positions of the mandible during sleep under therapy conditions. This would allow for check-up on the objective mandibular protrusion performed by the patient and therefore the progress of the titration of the OA_m.

To attach the plaster casts to the articulator, magnets were used that are incorporated into the articulator itself and that could not removed during the test. This could have influenced the output of the sensors tested. However, upon removing the magnets used for the positioning system, the sensors did not detect any magnetic field.

Further research could be directed towards the use of a single sensor instead of two. This would allow for further minimization and an easier construction of the monitoring system. Interchanging the MLX90333 for a MLX90363 could also improve the simplicity and exactitude of the measuring technique as the MLX90363 has three dimensions in which it can detect and measure the strength of a magnetic field.

Dimension of magnets and sensors used in this study allows for incorporation in an $OA_{m..}$ However, power supply and connectivity are important issues to take into account in any further design of a smart $OA_{m..}$

V. CONCLUSION

This study is a first step towards an optimized personal and automated monitoring system for the use of a smart and adjustable OA_m in the treatment of OSA.

The present results indicate that the use of magnetic sensors is a promising technique. The sensors used were capable of detecting and measuring the protrusion of the mandible with 0.5 mm accuracy at a fixed opening of 0.0 mm. A comparable accuracy for opening and lateral movements is yet to be obtained and further research is required as to the configuration, selection and/or development of adequate sensors.

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