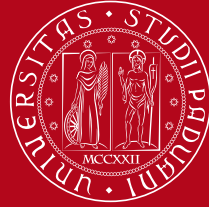


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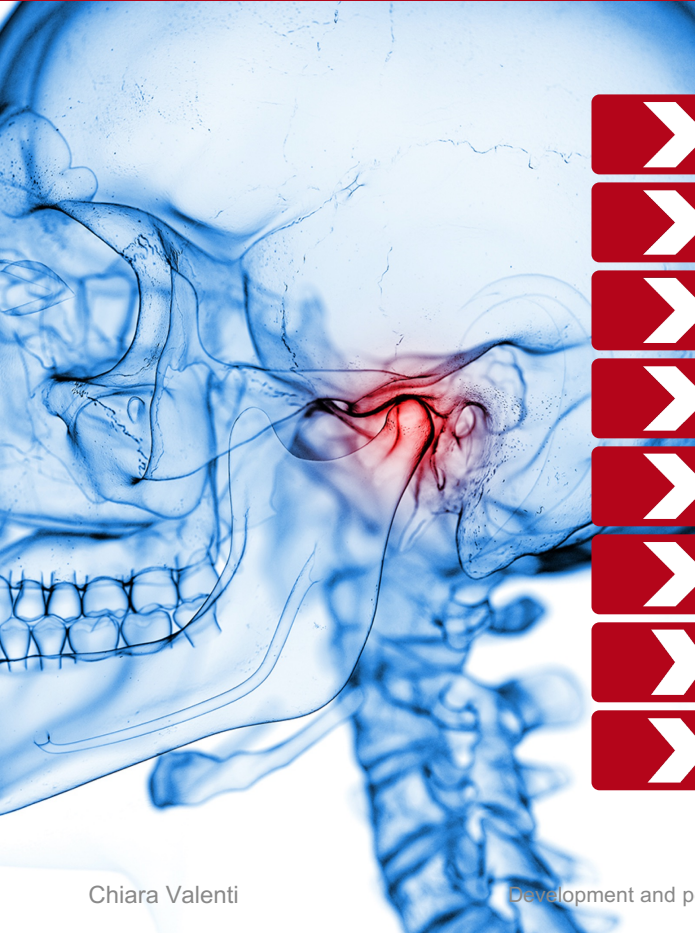
UNIVERSITÀ
DEGLI STUDI
DI PADOVA

Development and performance analysis of techniques for mandibular movement measurement.

Chiara Valenti - 39th Cycle

Supervisor: Prof. Gianluca Rossi

admission to 2° year - 16 / 09 / 2024



Introduction



Project



Objectives



WBS



First steps



Preliminary Results



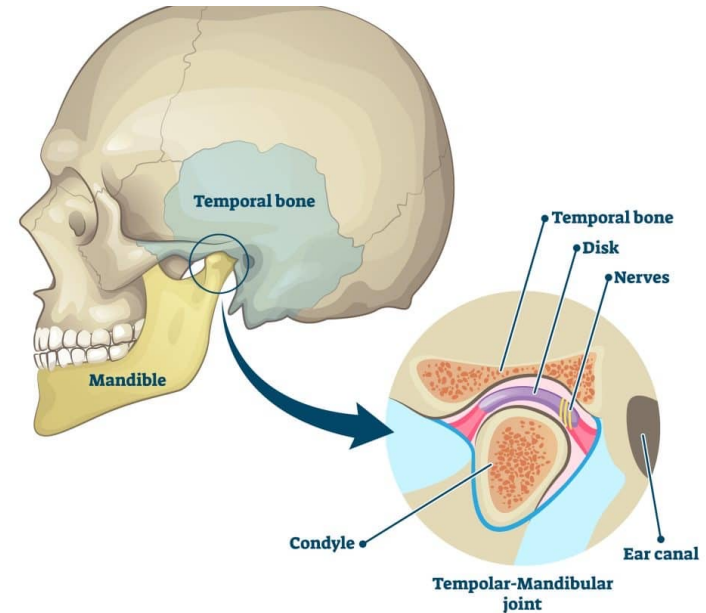
Posters, Conferences, and Publications

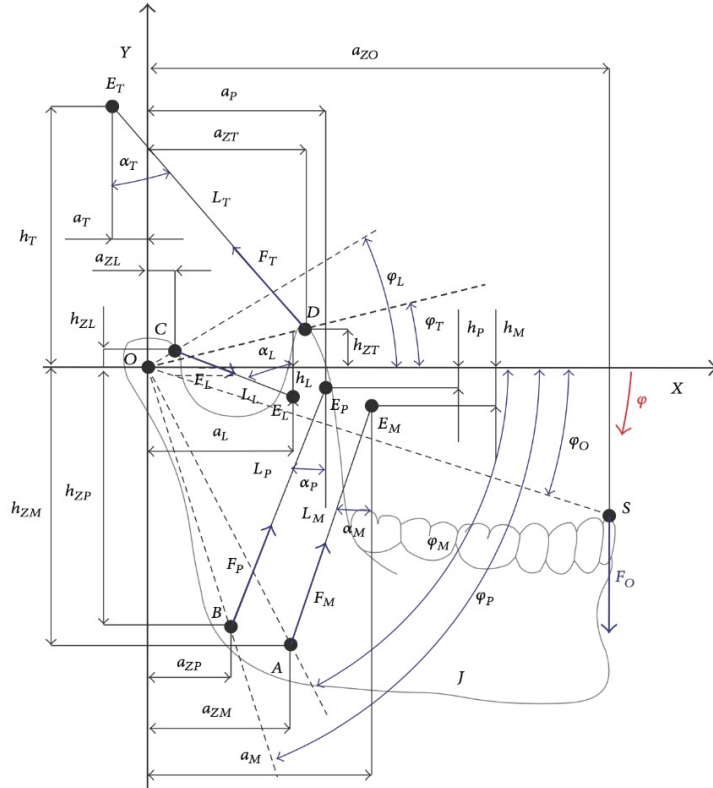


Gantt Chart

The measurement of the stomatognathic apparatus movements and masticatory tracings is a key element for the therapeutic approach of patients, to establish accurate diagnosis and effective treatment plans.

In particular for TMDs (temporomandibular disorders) characterization, as these pathologies include different conditions with complex etiology, therapeutic management, and differential diagnoses.





Jaw Tracking Systems (JTSs) have diagnostic and therapeutic purposes.

More approaches are needed to find a measurement method that meets realistic clinical needs.

This research is based on the development and analysis of a new accurate method for recording mandibular movements.

The aim is to design a novel, wearable device, resistant to motion artifacts, waterproof, unobtrusive for the patient, without ionizing radiation (CBCT), and with uncovered occlusal surface for mandibular movement measurement.

The objective of the research is to develop a prototype of jaw motion tracking system, and evaluate the measurement uncertainty both under in vitro and in vivo conditions.

Related expected benefits

- Realize accurate diagnoses of TMDs with effective treatment plans.
- Record data of physiological and pathological conditions for machine learning model training.
- Ensure a digital workflow, improving compliance, accuracy, efficiency, times, and costs of dental interventions.
- Personalize patient care with minimal post-production corrections of prosthetic or gnathological manufactures.

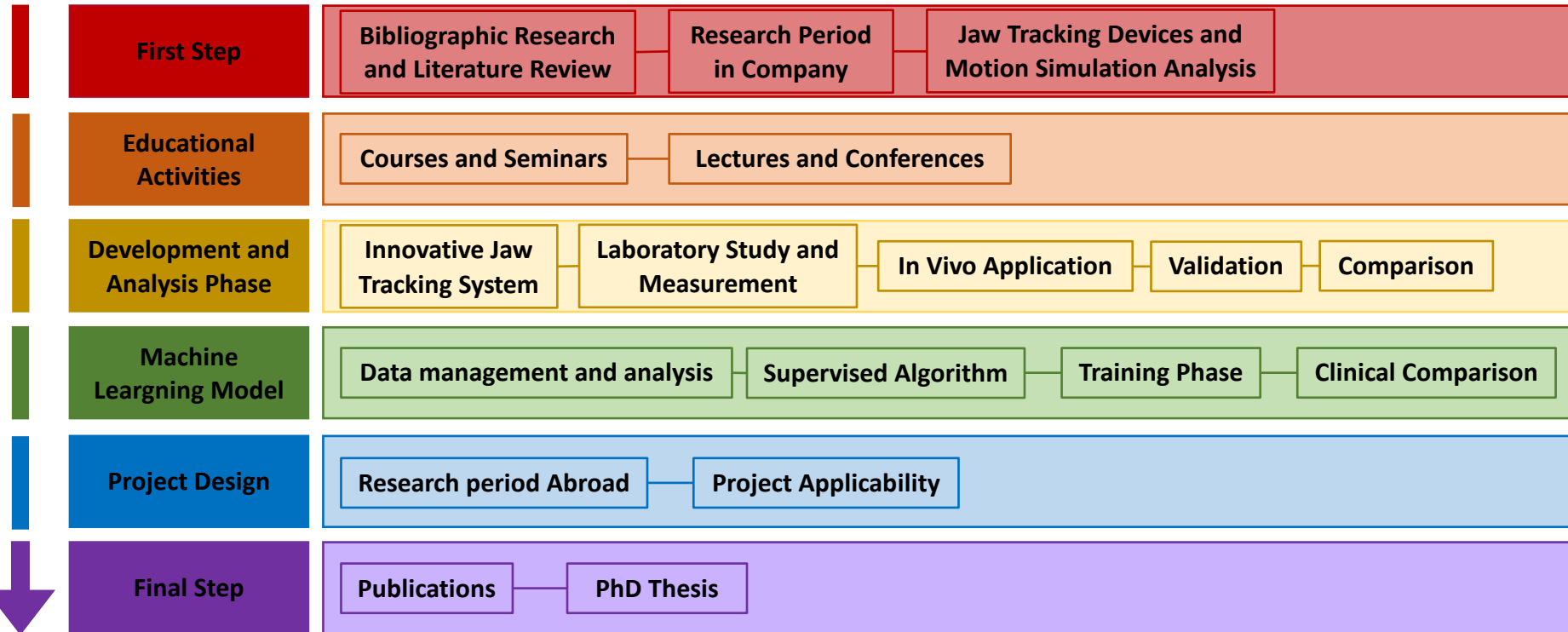


Chiara Valenti

Development and performance analysis of techniques for mandibular movement measurement.



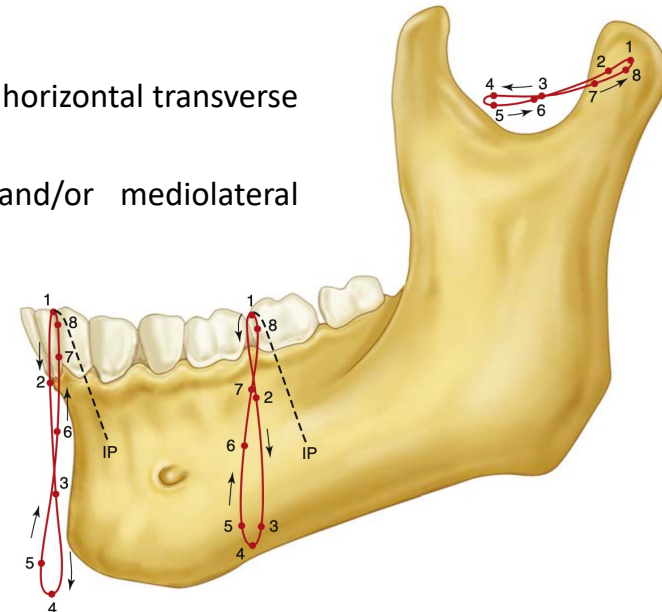
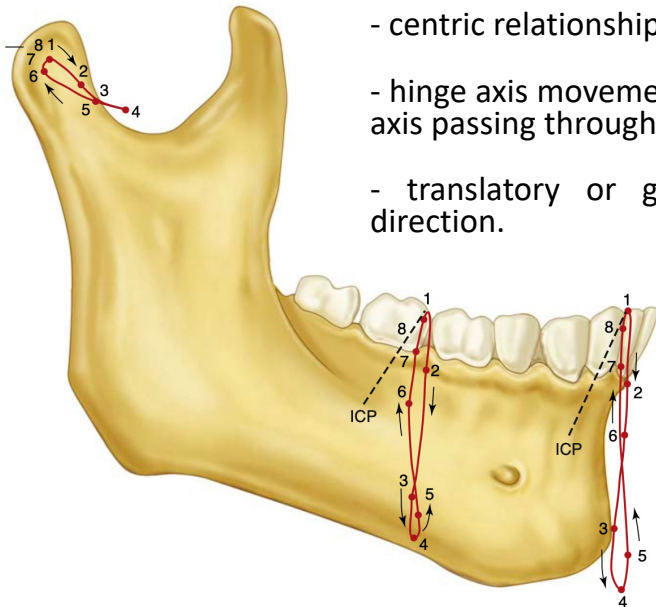
Working plan of the project



A review of the literature on the biomechanics was carried out, considering how mandibular movements are determined by an intricate kinematic system that includes different anatomical structures.

Key reference movements to be recorded:

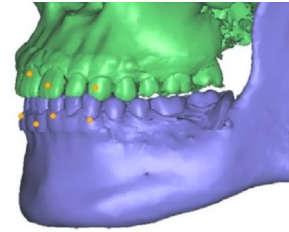
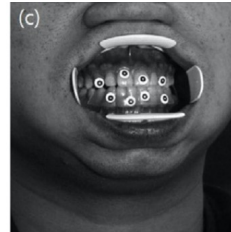
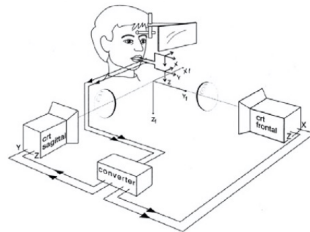
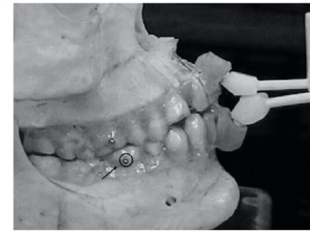
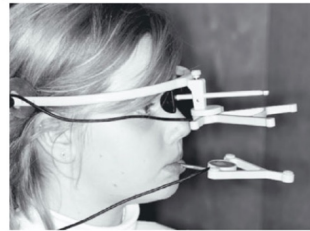
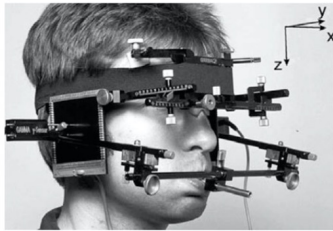
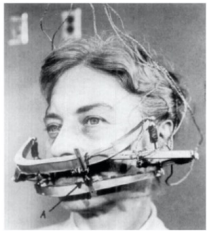
- centric relationship;
- hinge axis movement, a rotation of the mandible around the horizontal transverse axis passing through the heads of the condyles;
- translatory or gliding movement, in anteroposterior and/or mediolateral direction.



Jeffrey P. Okeson. *Management of Temporomandibular Disorders and Occlusion*. 8th Edition, 2019.

The characteristics of different JTS types, mandibular dynamics, and how it affects the production of dental manufactures, were studied in depth during the 3-months period in the dental lab.

Commercially available and experimental devices were analyzed, considering both in vitro and in vivo studies on healthy and/or pathological subjects, paying particular attention to the alterations of the tracings as the pathophysiological conditions changed.

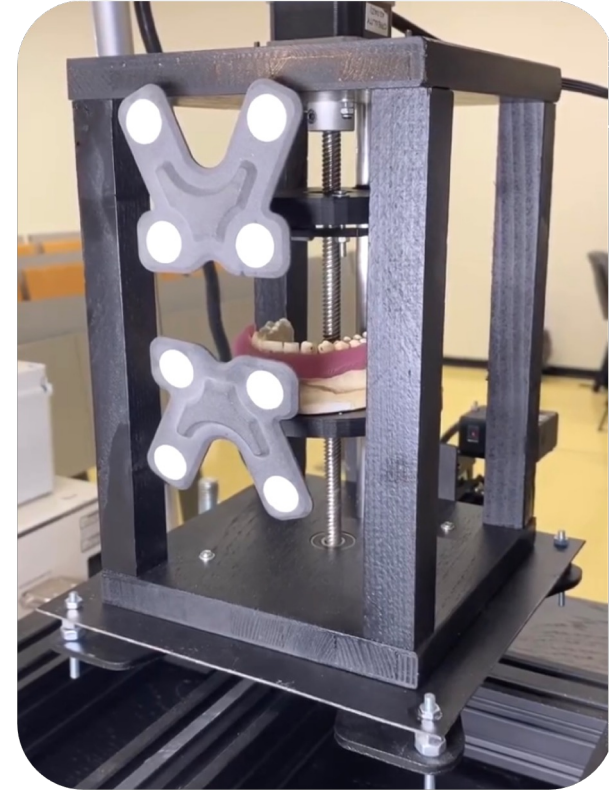


Woodford SC, et al. Measurement of normal and pathological mandibular and temporomandibular joint kinematics: A systematic review. *J Biomech.* 2020;111:109994.

To reproduce standardized linear motion along the y- and z-axes for the preliminary experimental setting, a simulation machine was built with parts of the structure and electronic components of an Ender 3 Pro 3D printer (Creality, Shenzhen, China).

The 3D printer's stepper motors, along with dedicated control drivers, were assembled to enable machine motion.

Linear movements were automatically defined using dedicated G-code motion functions stored on a microSD memory card, and repeated at a rate of 30 fps.



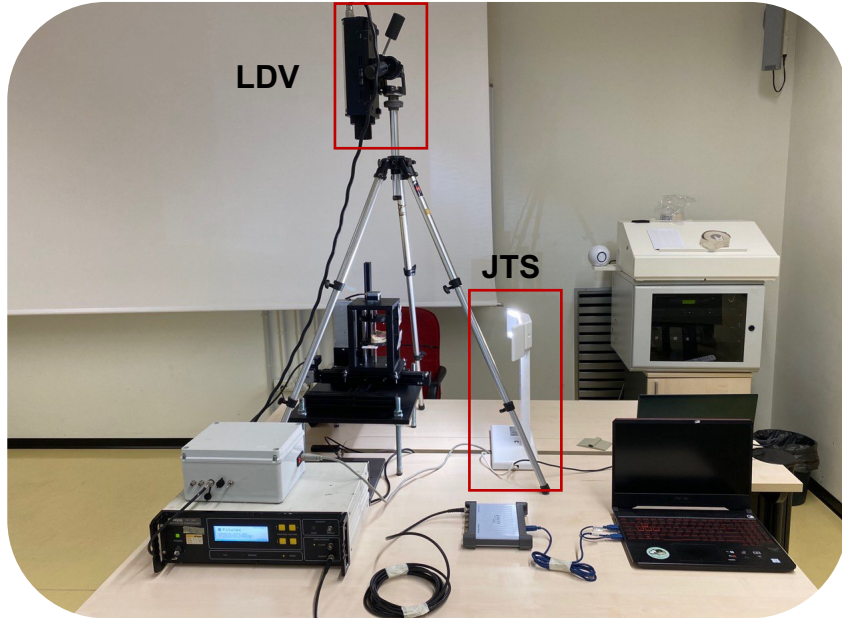


A new photometric JTS was selected to carry out preliminary measurement uncertainty analyses.

It was crucial to understand the accuracy of novel JTS in the market, to define its reliability and clinical utility, grasping any disadvantages, and making a comparison with the technique under development.

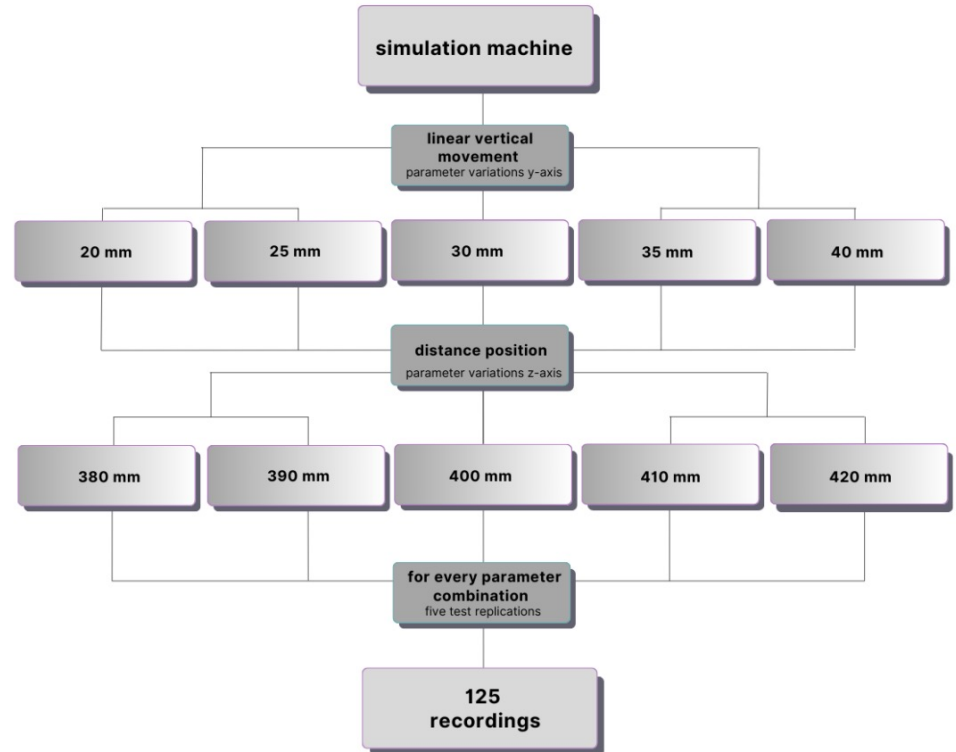
A Laser Doppler Vibrometer (LDV) was used as a reference to measure the vertical motion.

Laboratory Tests: preliminary results



EXPERIMENTAL PROTOCOL FOR MOTION RECORDINGS

CYCLOPS ————— LDV



Vibrometer Sensor Head Polytec OFV-303

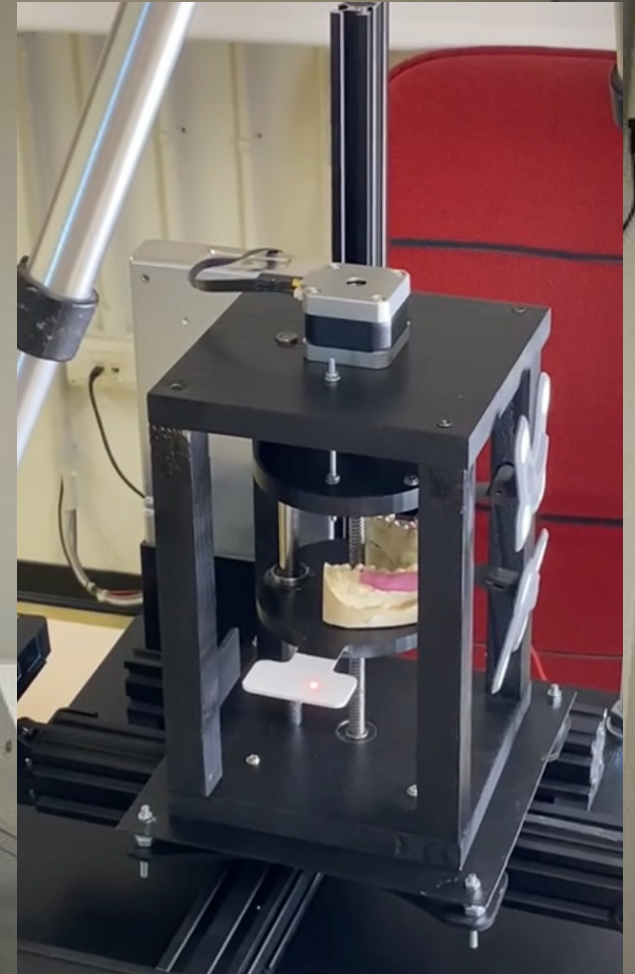
Laser type:	helium neon
Wavelength:	633 nm
Cavity length:	205 mm
Laser safety class:	II
Laser output power:	< 1 mW
Power consumption:	ca. 15W
Output center frequency:	40 MHz
Operating temperature:	+0°C...+40°C (32°F... 104°F)
Storage temperature:	-15°C...+65°C (5°F... 149°F)
Relative humidity:	max. 80%, non-condensing

Front lens ¹	Long range (QR)	Mid range (MR)	Short range (SR)
Focal length mm	100	60	30
Minimum stand-off distance ² mm	450	175	65
Aperture diameter (1/e ²) mm	12	7	3.5
Spot size (typ.) μm			
@ 175 mm	-	10	30
@ 450 mm	15	33	75
@ 1,000 mm	42	79	170
each additional meter	50	84	167
Maxima of visibility ³	232 mm + n · 205 mm, n = 0; 1; 2; ...		

¹ A label on the side of the sensor head shows the front lens model which is fitted.

² The maximum stand-off distance depends on the back scattering properties of the object. It can range up to 250 m for the sensor head OFV-303 and a surface with reflective coating.

³ Measured from the front panel of the sensor head.





Vibrometer Controller

Polytec OFV-3001



Mains voltage:	100/115/230 VAC \pm 10%, 50/60Hz, adjustable at the back panel
Power consumption:	max. 150 VA
Fuses:	1.0A/slow-blow for 230V 2.0A/slow-blow for 100/115V
Protection class:	I (protective grounding)
Operating temperature:	+5°C...+40°C (41°F... 104°F)
Storage temperature:	-15°C...+65°C (5°F... 149°F)
Relative humidity:	max. 80%, non-condensing
Dimensions:	450mm \times 355mm \times 135mm
Weight:	10.8kg
Calibration recommended:	every 2 years

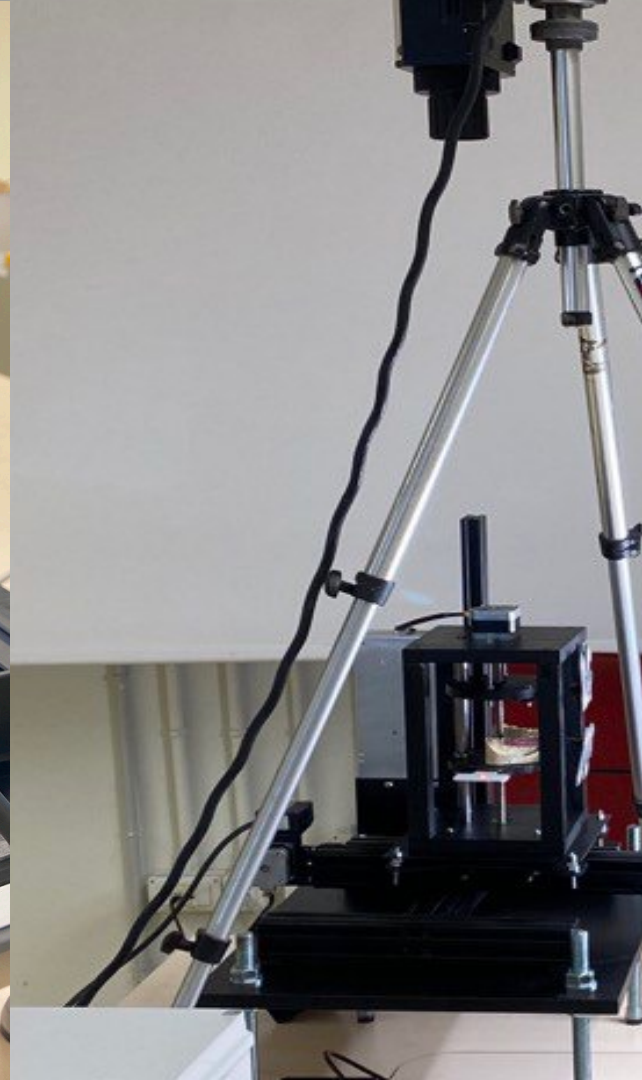
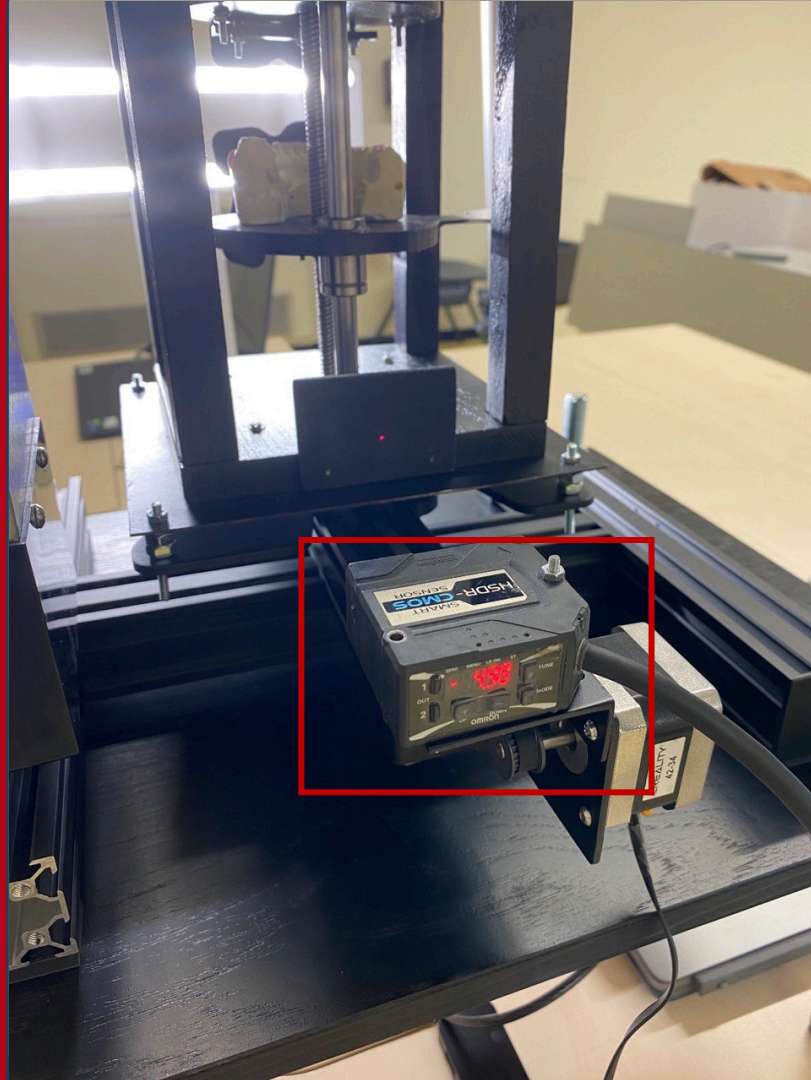
Displacement decoder	Measurement range (scaling factor)	Full scale output (peak-peak)	Resolution ¹	Maximum velocity	Bandwidth	Max. frequency for specified accuracy
			μm	m/s	kHz	kHz
OVD-10	20	320	0.08	2.5	0...250	100
	80	1,280	0.32	10	0...250	100
	320	5,120	1.3	10	0...250	100
	1,280	20,480	5.0	10	0...250	100
	5,120	81,920	20	10	0...250	100
OVD-20 and OVD-40	0.5	8	0.002	0.06	0...25	10
	2	32	0.008	0.25	0...75	15
	8	128	0.032	1	0...75	25
	20	320	0.08	2.5	0...250	100
	80	1,280	0.32	10	0...250	100
	320	5,120	1.3	10	0...250	100
	1,280	20,480	5.0	10	0...250	100
	5,120	81,920	20	10	0...250	100

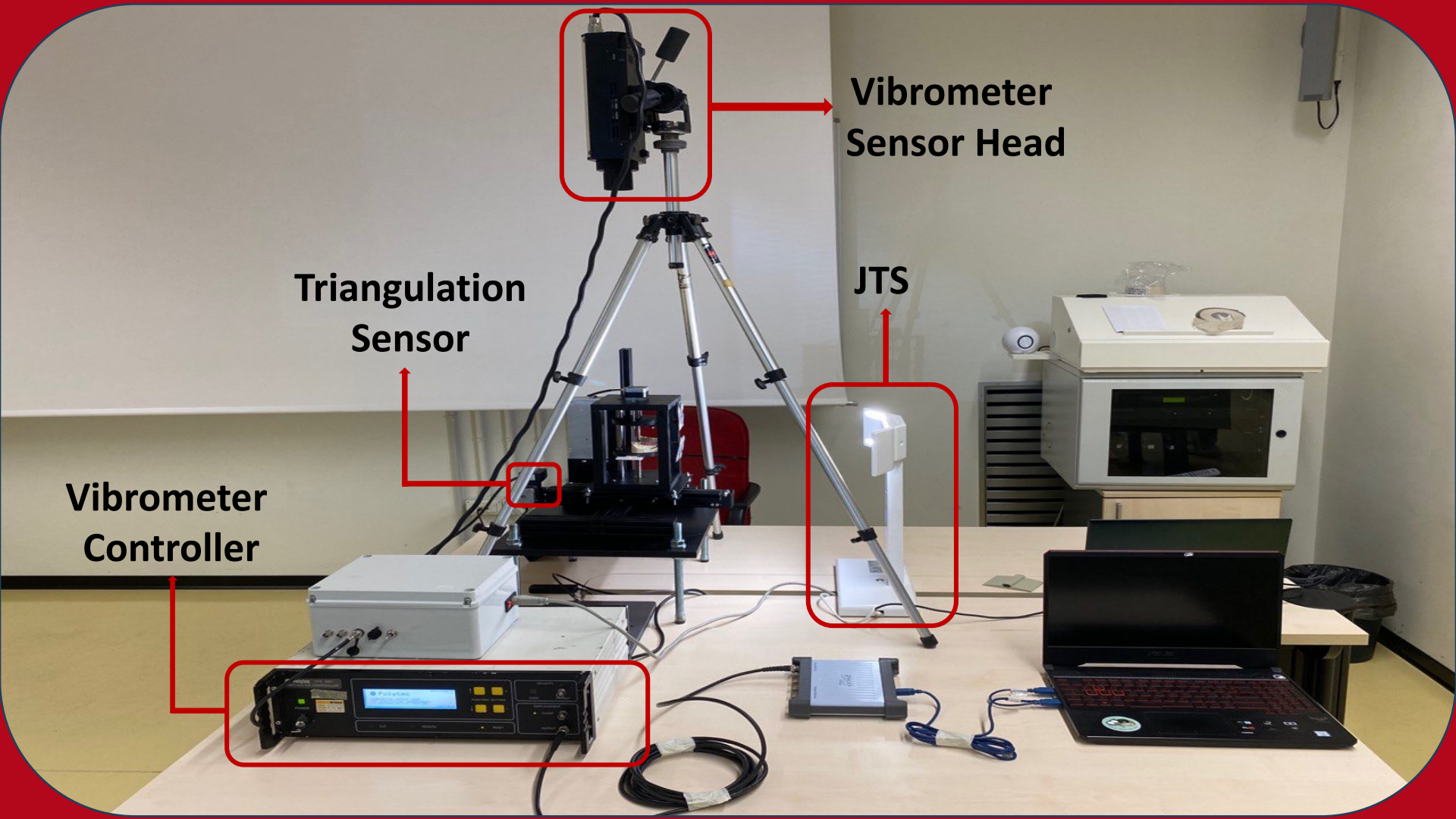
¹ The resolution is defined as 1 increment of the fringe counter output which is equivalent to a 4mV output voltage step.

Triangulation Sensor

ZX2-LD100L Line beam type
ZX2-LD100 Spot beam type

Measurement range	100mm \pm 35mm
Resolution	5 μ m
Linearity	Line beam \pm 0.05%F.S. ²
	Spot beam \pm 0.10%F.S. ²
Beam size	Line beam Approx.110 μ m \times 2.7mm
	Spot beam Approx.110 μ m dia.





**Vibrometer
Sensor Head**

**Triangulation
Sensor**

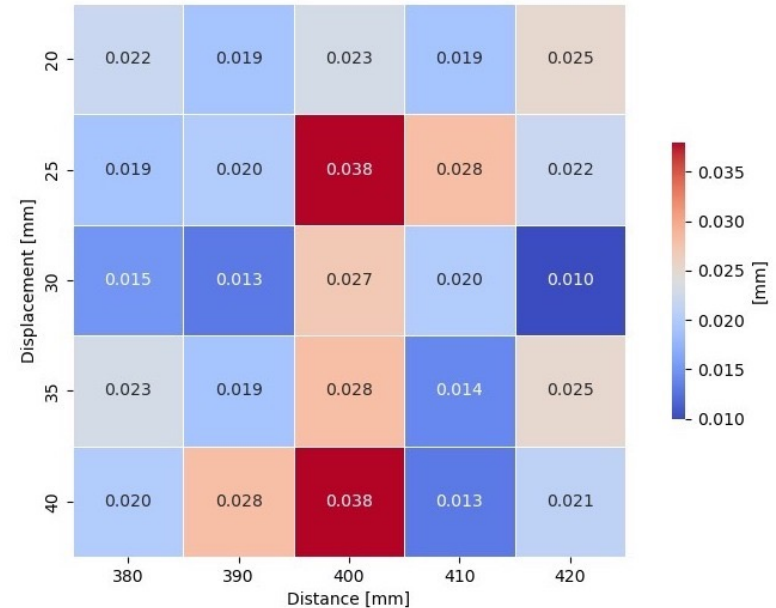
JTS

**Vibrometer
Controller**

Through a statistical analysis of random errors, the measurement uncertainty was performed calculating the SD of the mean over N repeated measurements of the same physical measurement.

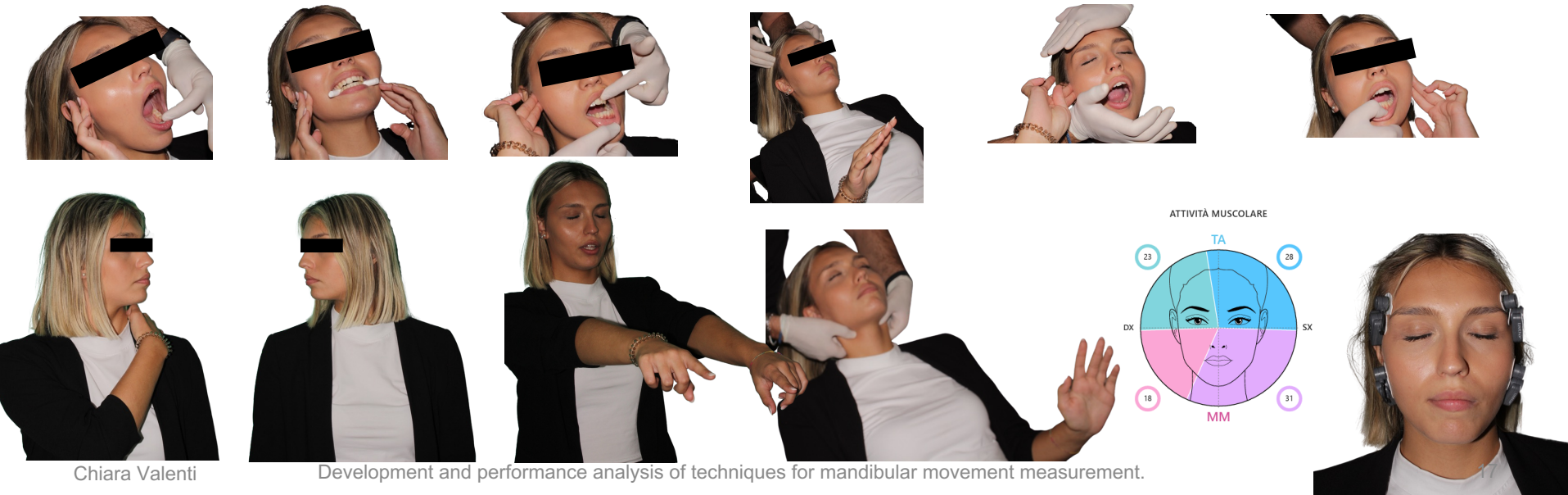
Data analysis was performed using Python with a $p = 0.05$ significance level.

Variations in linear vertical movement and distance positions did not significantly affect the accuracy of the instrument.

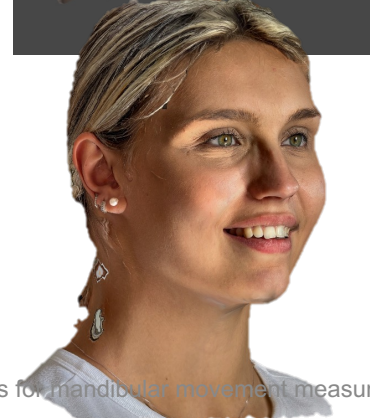
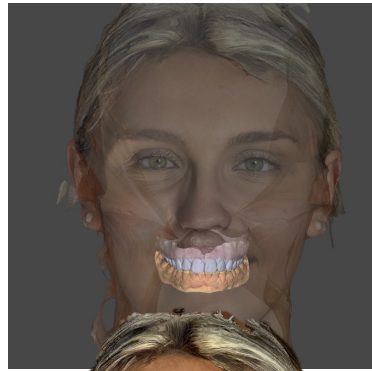


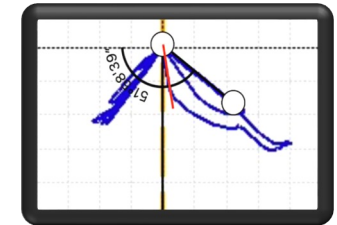
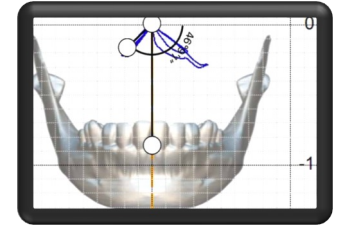
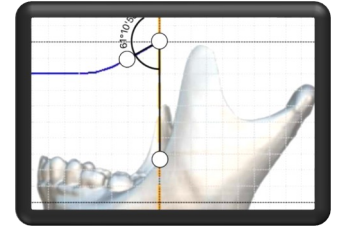
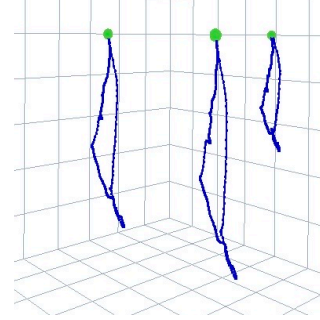
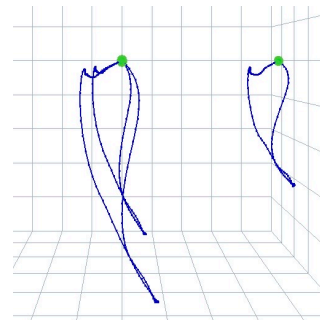
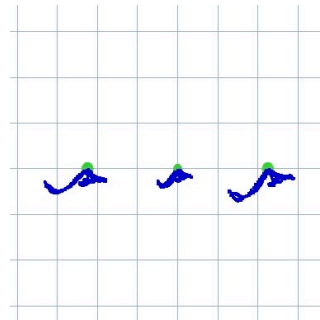
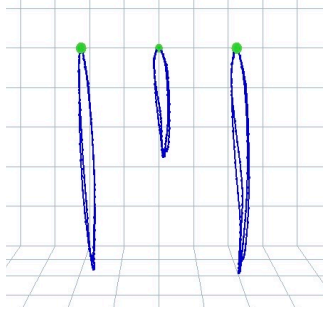
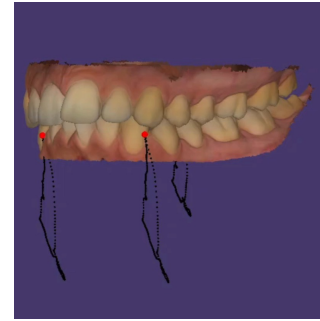
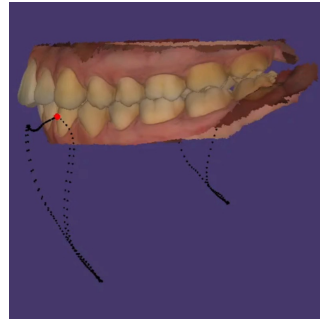
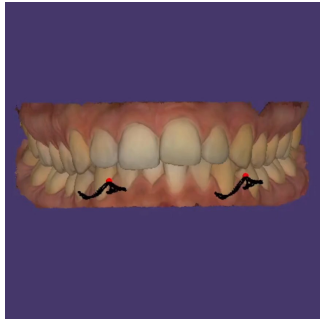
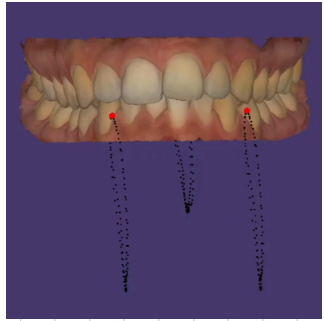
Preliminary in vivo tests were also carried out to evaluate the variability of functional movements in protrusion and mediotrusion.

20 subjects were included in the study after gnathological examination, then each participant performed 5 different recordings within one-month.



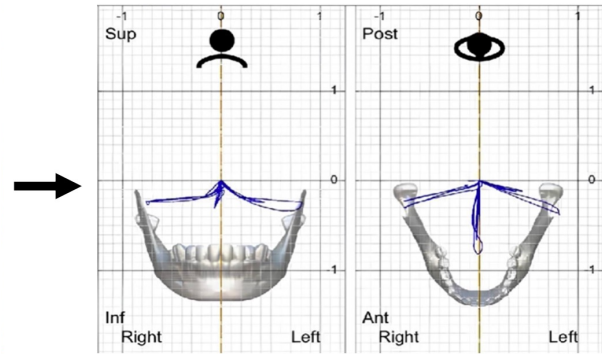
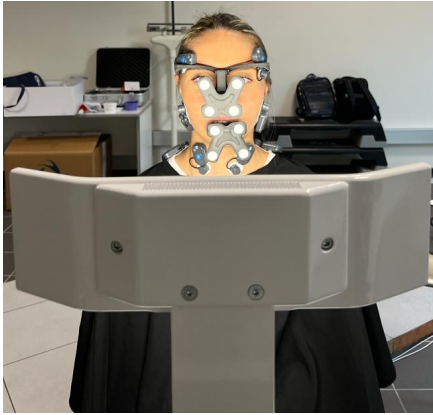
JTS recordings, facescans (Metascan), and intraoral registrations were made to superimpose 3D static information, the relationship between perioral tissues and dental arches, and mandibular dynamics and excursions.





The variability of movements was evaluated with the angle of functional paths within the first 2 mm from the maximal intercuspal position.

significant variations were reported between different patients, and non-negligible variations occurred even in the tracings of the same patient.

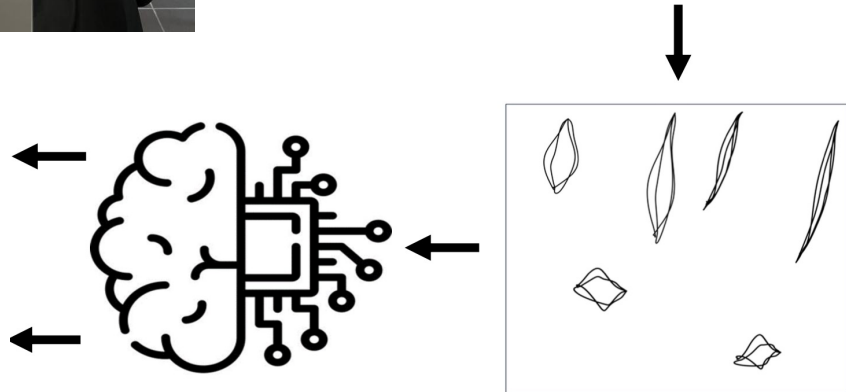


Recordings from 160 patients were converted from point clouds to 2D images to optimize the input.

80% of the dataset data were used for training, the remaining 20% for testing phase.

Healthy patient

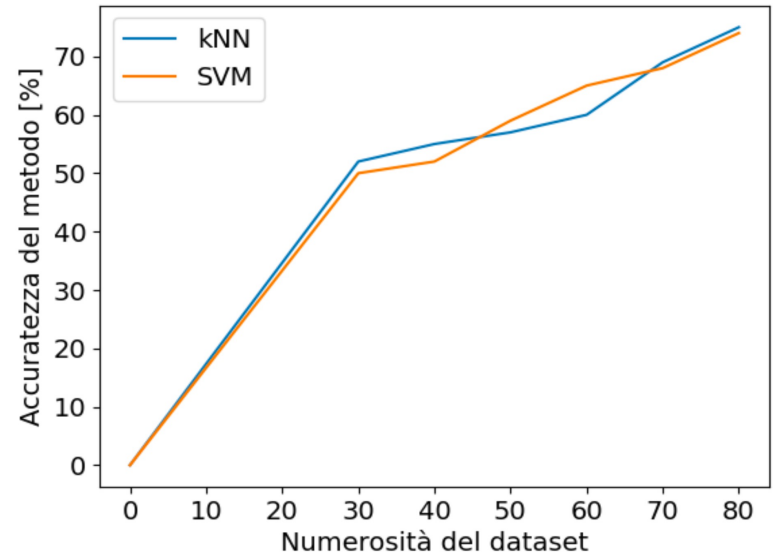
TMD patient



Classification algorithms implemented in Python:

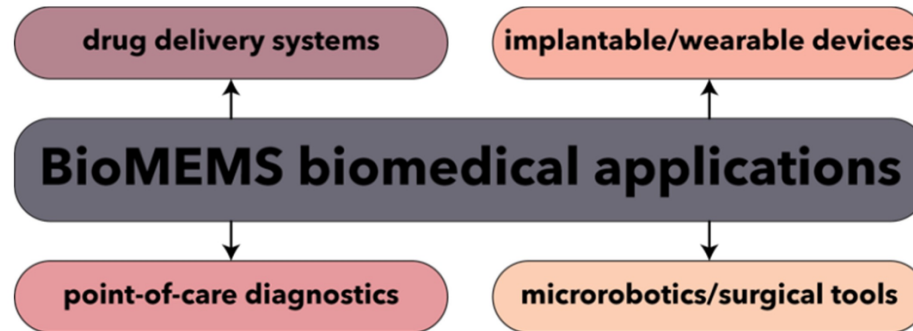
- k-NEAREST NEIGHBORSS (kNN) unsupervised algorithm determines the category of a new input comparing it with the features of the nearest neighbors in the dataset, and assigning the most common category among the selected neighbors.
- SUPPORT VECTOR MACHINE (SVM) supervised algorithm designed to identify the boundary that best separates image categories based on their distinctive features.

Future developments will consider to increase the database and explore convolutional neural networks (CNN).



Many options were evaluated for the development of a new JTS technique (ultrasound, optical, photometric, or magnetic systems).

The application of microelectromechanical systems (with integrated magnetometers, accelerometers, and gyroscopes), as in other biomedical fields, was identified as a potential system to record dental impacts through acceleration measurements, and jaw motion and dynamic closure, identifying pathological behavior that indicates the type of TMD dysfunction.



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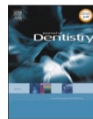


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Accuracy of a new photometric jaw tracking system in the frontal plane at different recording distances: An in-vitro study

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ARTICLE INFO

Keywords:

Kinesiology
Motion tracking analysis
Functional mandibular movement
Photometric jaw tracking system
Jaw movement recording

ABSTRACT

Objectives: To evaluate the accuracy of a new photometric jaw tracking system (JTS) in recording linear vertical movements in the frontal plane at different distances.

Methods: A mandibular plaster cast of a patient was placed on a simulation machine capable of linear movements along two spatial axes. Cyclops JTS (Itaka) was adapted to the plaster cast, while the head frame was attached to the simulation machine. The latter performed five linear movements from 20 to 40 mm in the y-axis; each movement was repeated five times at five different recording distance (380 to 420 mm). The recorded movements were measured and compared with those obtained with a laser Doppler vibrometer (LDV) for accuracy analysis. Data were statistically processed ($\alpha = 0.05$).

Results: No statistically significant differences were found between Cyclops and LDV measurements on the y- and z-axes ($p = 0.5$). Changes in linear vertical motion and distance positions did not affect the accuracy, which remained relatively constant with similar trends and values less than 1% for each parameter variation. The best condition observed was linear vertical movement of 30 mm at 420 mm (0.010 ± 0.023 mm).

Conclusions: Cyclops has proven to be an accurate JTS in recording linear vertical movements in the frontal plane at different recording distances. For optimal recordings, the scanner should be placed as close as possible to the markers; excessive vertical movements decreased the accuracy. However, this study has limitations and requires in-vivo confirmations.

Clinical significance: The tested JTS proved accurate in recording linear vertical movements in the frontal plane. However, given the limitations of the study, further investigation under real conditions is needed to support prosthetic and gnathological rehabilitations.

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Investigation of the precision of a novel jaw tracking system in recording mandibular movements: A preliminary clinical study

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ARTICLE INFO

Keywords:

Functional mandibular movement
Jaw tracking system
Kinesiology
Jaw movement recording, Computer aided design
Dynamic technical modeling

ABSTRACT

Objectives: This preliminary study aimed to clinically assess the precision of a novel optical jaw tracking system (JTS) in registering mandibular movements (MMs) of protrusion and mediotrusion.

Methods: Twenty healthy participants underwent recordings using Cyclops JTS (Itaka Way Med) for functional MMs of protrusion and laterotrusion by two trained clinicians. Each subject performed five registrations at different times according to a standardized pattern within one-month period. The angulations of protrusive and mediotrusive functional paths within the first 2 mm from the maximal intercuspal position (MIP) were calculated for each trace, using a data software for angle measurements. Descriptive statistics were used to assess the repeatability of the recordings for each participant and MM. Additionally, inferential statistics were carried out on standard deviation values obtained ($\alpha = 0.05$).

Results: The overall precision for all the patients was $7.07 \pm 3.37^\circ$ for the protrusion angle, $5.24 \pm 2.24^\circ$ for right laterotrusion and $5.14 \pm 3.06^\circ$ for left laterotrusion angles. The protrusion angle ranged from 3.08° to 13.57° , while the right and left laterotrusion ranged from 1.82° to 9.42° and from 1.58° to 10.59° , respectively. No statistically significant differences were observed between different functional MM types and gender ($p > 0.05$).

Conclusions: Recordings functional MMs of mediotrusion and protrusion using Cyclops JTS showed consistent repeatability, regardless of gender and functional MM type. The results revealed non-negligible variations that may be due to the patients' abilities to precisely reproduce jaw movements or to the operator's ability to consistently connect the kinesigraph.

Clinical significance: Capturing functional MMs digitally and importing the data into dental CAD software is essential for virtual waxing in prosthetic rehabilitations to design a functionalized adapted occlusion. Establishing the repeatability of MM recordings by a JTS is a crucial step in better understanding this novel JTS in the market. This process could facilitate the interpretation of cusp angles, aid in CAD dynamic technical modeling, and enhance clinical data communication between clinicians and technicians in a modern workflow.



L'Odontoiatria sostenibile e predicibile nel pubblico e nel privato



ACCURATEZZA DI UN NUOVO SISTEMA FOTOMETRICO DI TRACCIAMENTO DEL MOVIMENTO MANDIBOLARE SUL PIANO FRONTALE

Fusillo A.* Valenti C.^{ab} Di Pasquale F.^c Massironi D.^c Parretti S.* Grande F.^{ab} Capatano S.* Negri P.^c Eramo S.^c Pagano S.^c

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OBBIETTIVO

Lo studio si propone di valutare l'accuratezza (trueness e precision) di un nuovo sistema fotometrico di tracciamento delle dinamiche mandibolari (JTS) nella registrazione di movimenti lineari sul piano frontale, considerando diverse distanze di registrazione.



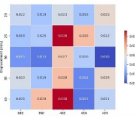
METODI



Un modello di arcata inferiore di un paziente è stato posizionato su una macchina da simulazione del movimento in grado di muoversi linearmente su due assi spaziali. La Mandylform di Cyclops (ITASA Way Med) è stata adattata al modello in genere, mentre l'Upper Positioner è stato fissato alla macchina da simulazione. I movimenti verticali lineari sul piano frontale da 20 a 40 mm sull'asse y sono stati eseguiti in quintuplicato a 5 diverse distanze di posizionamento (da 380 a 420 mm) del modello dal JTS Cyclops. Per l'analisi dell'accuratezza, i movimenti registrati dal JTS sono stati confrontati con quelli rilevati da un vibrometro laser di riferimento. I dati sono stati elaborati statisticamente ($\alpha = 0.5$) utilizzando il test ANOVA.

RISULTATI

Non sono state riscontrate differenze statisticamente significative tra le misurazioni eseguite con Cyclops e con vibrometro laser sugli assi y e z ($p = 0.5$). Il dispositivo mostrava condizioni migliori con un'ampiezza di movimento verticale pari a 30 mm od una distanza di 420 mm, evidenziando un'accuratezza complessiva di 0,010 mm. L'ampiezza dei movimenti verticali lineari e la distanza di posizionamento non hanno influito su l'accuratezza dello strumento; in generale sono stati riportati valori di accuratezza e precisione superiori al 99%.



CONCLUSIONE

Il JTS Cyclops ha dimostrato di essere un sistema accurato. L'accuratezza sembra essere più sensibile alla variazione dei parametri di ampiezza verticale che alla diversa posizione dello scanner durante le registrazioni. Per una buona pratica clinica, sarebbe meglio posizionare lo scanner il più vicino possibile al paziente in relazione al grado di apertura del soggetto, per facilitare il rilevamento dei marcatori durante i movimenti.

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ALGORITMO DI MACHINE LEARNING PER LA CLASSIFICAZIONE DELLE MISURE DEI MOVIMENTI DELL'ARTICOLAZIONE TEMPORO-MANDIBOLARE

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OBBIETTIVO

L'obiettivo di questo studio è sviluppare un algoritmo di machine learning per automatizzare la diagnosi delle disfunzioni dell'apparato stomatognatico, classificando i pazienti come "sani" o "con disfunzioni temporo-mandibolari". Per fare ciò, si impiegherà un dataset bilanciato di addestramento composto da tracciati digitali e analisi spettroscopiche. La necessità di questa indagine nasce dalle preoccupazioni di esperti del settore circa l'omogeneità dei soli traccati mandibolari, al fine di una diagnosi accurata.

METODI

I pattern mandibolari (vi) impagati appartengono a 160 pazienti, equamente ripartiti tra individuali sani e con disfunzioni temporo-mandibolari. Tali traccati sono stati prima acquisiti tramite un sistema di Jaw-Tracking per convertire da tavolo di punti ad immagini bidimensionali (2D) per ottimizzare i formati per i modelli di machine learning. L'80% dei dati del dataset è stato destinato all'addestramento dei modelli, mentre il restante 20% alla fase di test. Gli algoritmi di machine learning sono stati sviluppati e implementati utilizzando il linguaggio di programmazione Python.

k-NEAREST NEIGHBORS (kNN)

Questo algoritmo di classificazione determina la categoria di un nuovo input confrontandolo con i dati più vicini nel dataset. Nella specificazione delle caratteristiche del dato da classificare e la confronto con quelli circostanti, identificati come "k" vicini più prossimi. Quando applicato ad immagini bidimensionali, non compare le caratteristiche assegnate al categoria più comune tra i vicini selezionati. Questo approccio rende il kNN ideale per problemi di classificazione con relazioni spaziali tra i dati.

SUPPORT VECTOR MACHINE (SVM)

L'SVM è un algoritmo di classificazione atto ad individuare una linea di separazione (o un piano iperdimensionale) che divide due gruppi di dati con il massimo margine possibile. Per ogni nuovo dato da classificare, l'SVM determina il confine che minimizza la distanza tra le classi, minimizzando al contempo gli errori di classificazione. Nel contesto delle immagini bidimensionali, viene tracciato il confine che meglio separa le categorie delle immagini in base alle loro caratteristiche distintive.

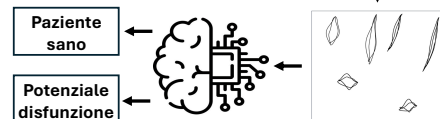
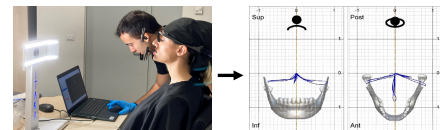


Figura 1. Acquisizione dei movimenti di ATM (articolazione temporo-mandibolare), elaborazione dei dati, comparazione tra due algoritmi di machine learning e classificazione di paziente sano o con potenziale disfunzione.

RISULTATI

Si osserva come l'uso degli algoritmi considerati abbia ampia margine nella robotizzazione dei dati, con un'accuratezza di un'operazione, migliorando l'efficienza complessiva.

L'algoritmo k-Nearest Neighbors (kNN) ha infatti raggiunto un'accuratezza del 79%, mentre per il Support Vector Machine (SVM) si parla del 74,58%, dimostrando una buona capacità nel classificare correttamente i traccati mandibolari.

CONCLUSIONI

Differenziate dalla consolidata prassi dei professionisti, gli algoritmi di machine learning applicati in questo studio hanno dimostrato un notevole potenziale nell'automatizzare la classificazione di pazienti sani e affetti da disfunzioni temporo-mandibolari.

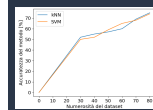


Figura 2. Accuratezza dell'automazione dei dati.

Dal grafico (Figura 2) è possibile osservare come l'accuratezza dei modelli aumenti con la mancanza dei dati di test, infatti, più dati sono disponibili per l'addestramento, maggiore è la precisione nella classificazione. Questo suggerisce che un ampliamento bilanciato può ulteriormente migliorare le prestazioni diagnostiche. Gli algoritmi k-NN e SVM puntano quindi ad aumentare la numerosità del database che è ritenuto a disposizione, cercando anche di includere una maggiore varietà di soggetti. Inoltre, verranno esplorati nuovi algoritmi, come le reti neurali convoluzionali (CNN), per migliorare ulteriormente la capacità di riconoscimento delle caratteristiche complesse dei traccati e aumentare la precisione diagnostica.

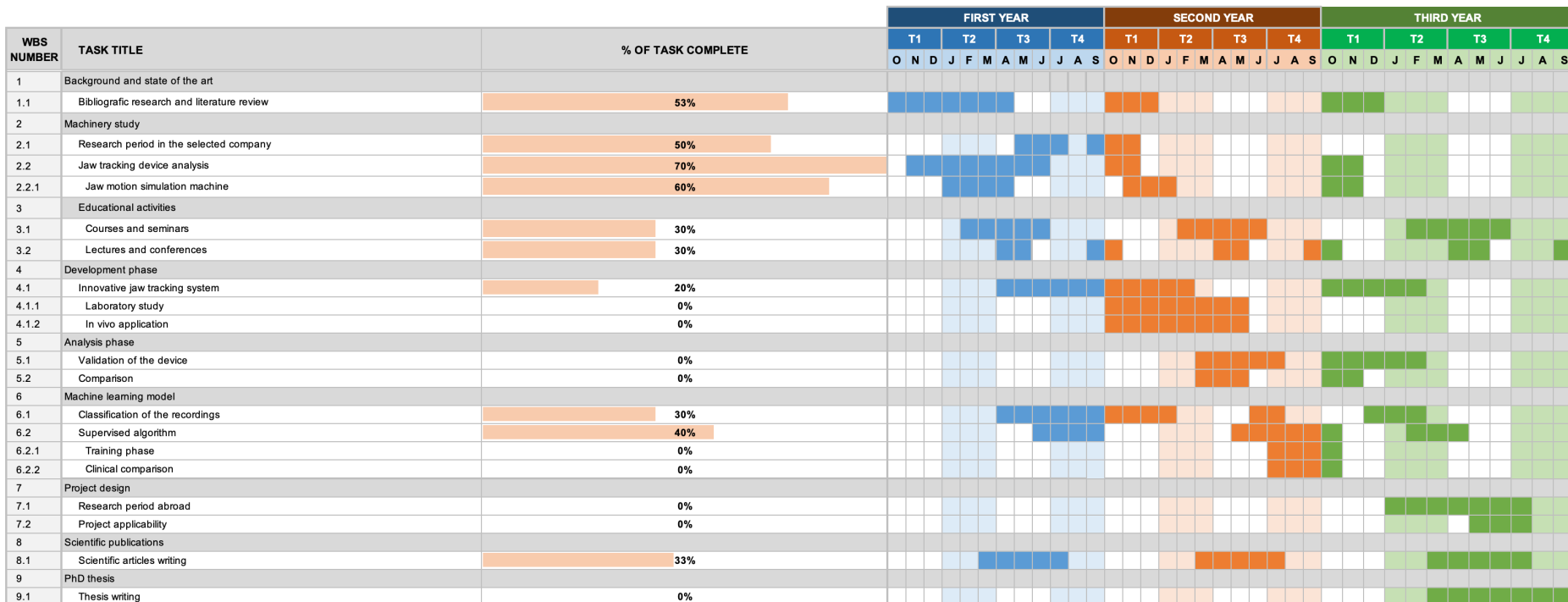


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