Title:
Development of Digital Articulator and its Accuracy Verification using Optical Measurement

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Introduction:
In dentistry, the correct prostheses should be made with the correct occlusion poses. Dentist and dental technician usually design the fixed or removable restorations with mechanical articulators which can simulate mandibular movements and the occlusion to prevent the occlusal interference or other problem. Recently, with the development of dental CAD/CAM systems, commercial software can now digitalize traditional dental workflow and the user can design restorations with higher quality and much less time. However, the occlusion of opposing teeth should be considered for a correct prosthetic design. Therefore, there should be a digital articulator to simulate mandibular movement and occlusion in digital environment.

The first articulator in U.S. patent is created by Dr. Daniel T. Evens [3] 1840. In 1895, most of researchers considered that there is a condylar path with an inclination and developed average articulators[2] which make condylar ball move with a fixed inclination. In 1899, Snow created facebow to measure the information about human's skull and transfer that into articulator to make sure the plasters of the upper jaw and the lower jaw are mounted in the correct position[2]. In 1910, Gysi [4] developed an adjustable articulator with adjustable condylar guidance. In 1997, Szentpetery [4] created a digital articulator to simulate digitized occlusal surfaces. In 2002, Kordass and Gaertner [3] used Jaw Motion Analyzer (JMA) to record jaw movement and simulated the movement in the computer with static and dynamic occlusal collision displayed. Nowadays, there is commercial digital articulator like Ceramill Map 300 CAD/CAM system by Amman Gribach and Debtak System by 3Shape and exocad by exocad GmbH. However, most commercial systems today do not have verification methods to show the accuracy of the simulation. Therefore, it is questionable whether they can be truly useful in determining the correct occlusion when it comes to designing prostheses.

This paper presents the development of a virtual digital articulator by analyzing the kinematics of the Artex Non-Arcon CT semi-adjustment articulator which can be used in about 95% prosthetic cases and developing the forward and inverse kinematic model. As the digital articulator moves, the digital upper teeth move relatively to the digital lower teeth, thus simulating the occlusal path with teeth collision function. To verify that our digital articulator can simulate the mechanical articulator with adequate accuracy, we develop an optical tracking method[5] to measure the pose of mechanical articulator with 6 degrees-of-freedom and compare that with the digital articulator. The result shows that the digital articulator can simulate the jaw movement with sufficient accuracy and hence can be properly used for teeth occlusion evaluation.

Main Idea:
Fig. 1 shows the flowchart of the proposed digital articulator system. First of all, the digital articulator needs to be modeled by building the CAD model with 3D measurement and analyzing the kinematics

and dynamics of the mechanical articulator. In this work, we use a very popular Artex Non-Arcon CT semi-adjustment articulator to build the model. Using this digital information, the second step is to load digital teeth casts which are scanned by a 3D scanner and fed into our digital articulator system. Next step, we can adjust the condylar inclination angle and Bennett angle at the right and left sides of the articulator and move the upper teeth with the upper part of the digital articulator along with the incisal guide which represents the default occlusal path of the mechanical articulator. As the upper jaw is moving, our system can detect the collision between the upper teeth and the lower teeth. If both teeth collide, there is an interference. The developed digital articulator will correct the default path to avoid interference and display the result on the screen for the user. In this way, our system can simulate the movement of the jaw after digital restoration is put into the mouth and the user can check whether the designed restoration will cause undesirable occlusal interference or other problem.

To verify the accuracy of our digital articulator, we develop a method to compare the pose of the mechanical articulator and the digital articulator with camera and marker tracking. Fig. 2 shows the flow chart of the optical authentication method for the digital articulator's accuracy. At first, we mount two casts on the articulator and use the optical scanner to scan the surface of the mechanical articulator with the mounted casts, and transfer this position relationship into the digital articulator. We can, therefore, make sure the position of casts in the mechanical articulator are the same with the digital casts in the digital articulator. Secondly, we move (open) the mechanical articulator and fix its position, and use the scanner to scan the upper teeth and lower teeth. The position information of two casts can provide the transformation from the closed position (center occlusal position) to the moved position. Meanwhile, we track the markers which are attached to the mechanical articulator to measure the position of the incisal pin which can provide the corresponding transformation by the kinematic model we analyze. Comparing two transformations, we can obtain the error between the digital and mechanical articulator.

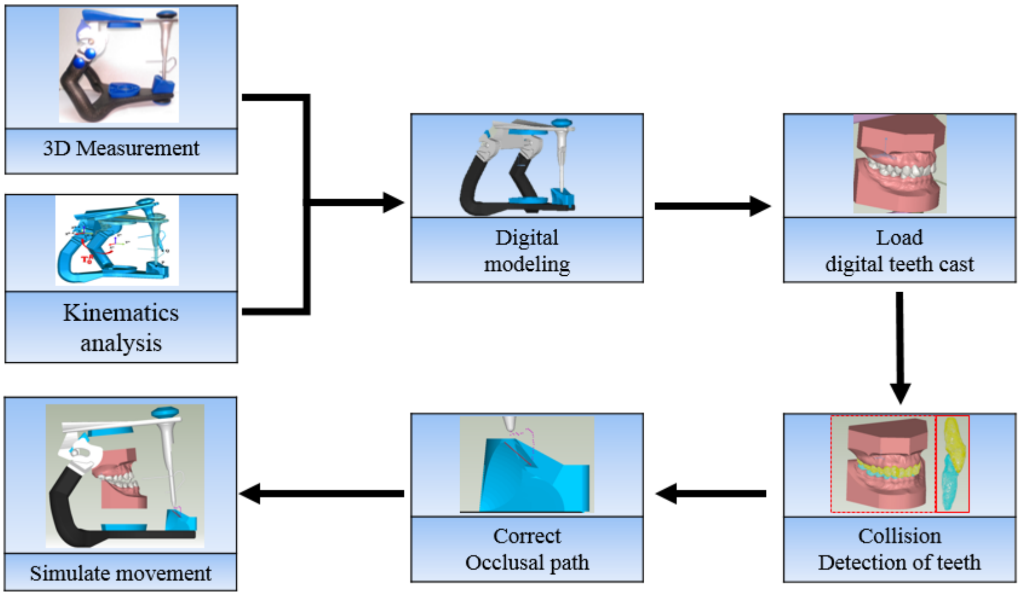

Fig. 1: Flow chart of the system.

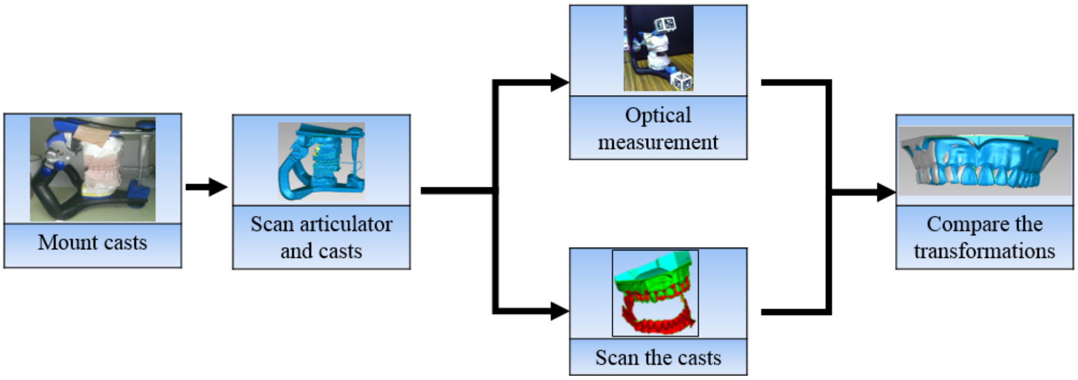

Fig. 2: Flow chart of the optical authentication method.

Conclusions:

We develop a digital articulator which can simulate mandibular movement between opposing teeth and develop an optical tracking method to verify the accuracy of the digital articulator. We provide dentist and dental technician a solution to simulate the mandible movement of patient in digital environment and can combine with other dental design software to satisfy a digital dental workflow. The digital articulator system proposed in this paper is described as follows:

1. Digitalize the mechanical articulator. User can simulate the mandible movement in the digital environment. By the combination with other digital dental software, user can design their restoration in the digital environment which is more efficient and accurate.
2. Collision detection provides a correct occlusal path with the interference between upper teeth and lower teeth when the digital articulator moves.
3. We provide an optical tracking method which can compare the movement error between the mechanical articulator and digital articulator. Thus the accuracy of the digital articulator can be verified.

We measure our system accuracy in five different poses and the result is shown in Tab. 1. In the result, the error of our system is under 1mm in translation and 1 degree in rotation which provides sufficient accuracy for the user to check the design of restoration under static and dynamic occlusion conditions.

	Big open mouth	Small open mouth	Right lateral	Left lateral	Protrusion
Average rotation error (degree)	0.65	0.49	0.58	0.23	0.41
Average translation error (mm)	0.95	0.78	0.70	0.74	0.68

Tab. 1: Accuracy verification of the digital articulator.

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