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Measuring tooth movement in 3D

Resolution, accuracy and reliability of the optical motion capture system

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Abstract- **This paper presents the development of a novel application using motion analysis techniques to measure tooth movement in 3D. Measuring the relative displacements of teeth under load allows a greater understanding of the mechanical properties of the periodontal ligament (PDL). Two marker clusters were fixed onto the measured tooth and the reference tooth via orthodontic brackets and movements were captured using two 60 Hz infrared cameras. Software was modified to calculate 3D tooth displacements and rotations. The development of this system will provide reliable data for modelling the periodontal ligament (PDL). It is therefore important to evaluate the measurement system characteristics.**

- **System accuracy, defined as % max. absolute error / measurement range, was 2.13 % using spherical markers and 1.5 % using diamond markers for a measurment range of 20-200μm.**
- **System resolution, defined as minimum step size that the system could accurately detect, was 10μm.**
- **System noise band was 5.76μm**
- **System repeatability, defined as max. st. dev. in the measurement range, was measured in the x, y and z directions on different days (light intensity and temperature), five times, using step up and then step down measurements for the same step size and was range from ±1.7μm to ±3.9μm.**

These results demonstrate that the system is sufficiently accurate to measure tooth displacements (120- 160 μm) and could potentially be useful in many other applications.

Keywords-component; tooth movement, system accuracy

I. INTRODUCTION

Optical motion analysis systems have been widely used in biomechanics with previous investigators focusing pose, gait and movements of the human body in a larger field of view [1- 8]. A Qualisys (Sweden) Mac Reflex 3D motion capture system was used to measure deformations of dental implants under load [9]. In principle, optical motion analysis systems could be capable of very accurate measurements, providing appropriate optics and calibration techniques are used, and there may be many applications in strain and deformation measurement in biomechanics and other areas of engineering.

It is on this basis that the Qualisys (Sweden) Motion Capture System has been applied to define the loading response of teeth to study the mechanical properties of the PDL by measuring the small relative displacements of the tooth under load. The PDL is a soft tissue, which connects the root of the tooth to the alveolar bone (Fig.1). The PDL consists of blood vessel and collagen fibres embedded into alveolar bone. The biological structure of the human PDL is very complicated and its mechanical properties such as viscoelasticity, poroelasticity and anisotropy, are not well understood due to the fact that in-vivo specimens are very small and dehydrate quickly, thus preventing mechanical testing. There is considerable evidence to show that deformation of the PDL has a key influence on orthodontic tooth movement [10, 11, 12, 13] and measuring tooth movement in 3D space, thus deforming the PDL provides a practical approach to understanding the mechanical properties of PDL.

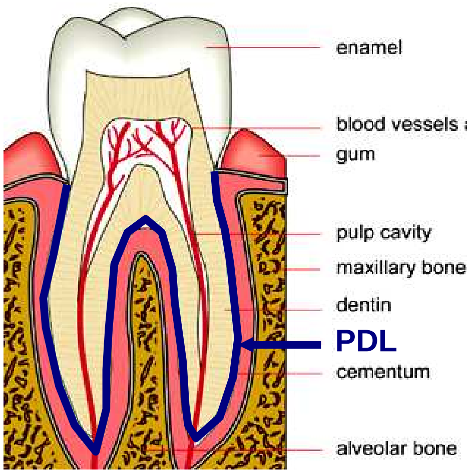


Fig.1 The structure of root of tooth [14]

For measuring tooth movement, the developed method uses two external marker clusters attached onto the measured tooth and the reference tooth. 3D tooth rotation and translation is calculated using software previously developed to measure knee and spinal [7]. In order to define the accuracy of the motion capture system in detecting small marker displacements, the Qualisys (Sweden) optical motion capture system characteristics were evaluated, specifically focusing on the following questions: What is the actual resolution of the system in a small field of view? How accurately does the system measure small displacements in three orthogonal directions? How repeatable are the displacement measurements? What are the noise characteristics of the system? How is the system used to measure the tooth movement?

II. METHOD

The optical motion analysis system used comprises two 120 Hz infrared cameras (Qualisys ProReflex, Sweden) and associated software. For accurate measurement in a small field of view, the lenses have a longer focal length than is normally used for gait analysis, so that cameras can be positioned at a more appropriate distance. The two cameras were placed as close as possible to the markers to maximise the system resolution. Two cameras created a 68.18 x 51.14 mm overlapped field of view. The camera system was calibrated using a static frame calibration method instead of the conventional wand calibration. This is because wand calibration is difficult when defining such a small measurement volume since the markers occupy a large proportion of the field of view and are easily obstructed. For the calibration frame, Mitutoyo Coordinate Measurement (MCM) equipment was used firstly to determine one marker as origin in 3D space, then to define the 3D positions of other markers relative to the origin marker. The 3D coordinates of the marker positions were used as the software standard to calibrate the camera system. The calibration frame was designed to be $20\times35\times20$ mm (Fig.2) and system coordinates were defined with the calibration frame horizontal direction as the x-axis, vertical direction as the y-axis with the z-axis perpendicular to x y plane.

The system characteristics were evaluated using a National Physical Laboratory (NPL) wedge type comparator with a resolution of 0.25µm as a standard. To compare the system characteristics for the different marker profiles, 2×4 mm diamond markers and 2.5 mm diameter spherical markers were used. These were attached to the moveable head of the comparator for measuring the displacement respectively. The comparator was rotated to measure along different axes.

Experiments involved two markers, which were moved in ten steps along each axis with the infrared cameras detecting their displacement. The whole process was repeated five times on 5 days under the different light intensity and temperature. Every point was sampled for two seconds at a sampling rate of 60Hz, giving 120 frames of data for each point.

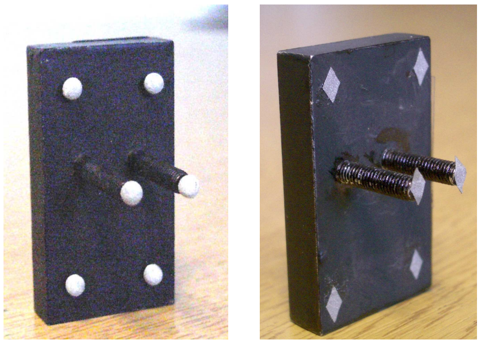


Fig. 2. The calibration frame with 2.5mm diameter spherical markers and 2×4 mm diamond markers.

The actual measured step, its mean value, error, and actual measuring step divided by ideal step were calculated as a percentage. This percentage was used to evaluate the actual resolution of the system.

The resolution was defined as the minimum step size that the system could detect.

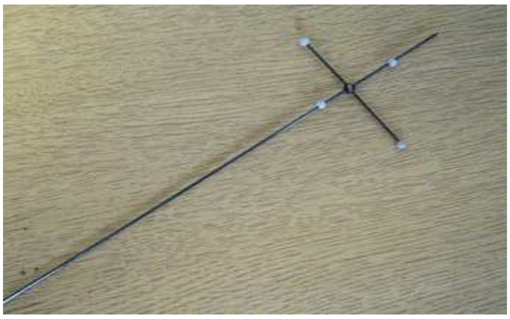
The system accuracy was defined as the maximum absolute error in the range divided by the measurement range, expressed as a percentage.

Repeatability was evaluated by repeating the step up and step down measurements in each direction five times on different days, under different temperatures and light intensity. The standard deviation of the measurements was calculated as a measure of repeatability.

Random noise in the system was measured by sampling a static marker for 28800 frames over four minutes, repeated five times, and calculating the mean and error of the 3D marker position. The error expressed the system random noise including ambient vibration, temperature drift and time drift in the signal processing circuit.

The relative measurement method is used to measure tooth movement. Two marker clusters are fixed onto the measured tooth and the reference tooth via modified orthodontic brackets (Fig. 3a). Static measurements using a pointer with four markers are recorded for three landmarks on the tooth to be loaded (Fig. 3b). Under loading in the vertical and horizontal directions and in axial twist, the locations of the two marker clusters are captured.

(a)



(b)

Fig. 3. The relative measurement method uses: (a) Two marker clusters fixed onto the measured tooth and the reference tooth via modified orthodontic brackets and; (b) a pointer with four markers.

In- house software calculates the change in relative position between the moving marker cluster and the reference marker cluster using transformation matrices and a modified Grood and Suntay Joint Coordinate System approach [15]. A software block diagram is shown as Fig.4.

III. Results and Discussion

The system accuracy was evaluated, shown as Fig.5. The system repeatability was found to be ±1.7μm, ±2.3μm and ±1.9μm for the diamond markers, and ±2.6μm, ±3.9μm and ±1.9μm for the sphere markers in x, y and z directions respectively. The system resolution was found to be 10 μm in the 68.18×51.14 mm field of view. The system random noise level (defined as the st. dev., equal to the RMS amplitude) was 1.47μm. The noise band, defined as 3.92σ, was 5.76μm.

In the 68.18×51.14 mm field of view, the system resolution was 10μm, which is higher than the theoretical value of 1/60,000 of the field of view (1.14μm) given by the manufacture's technical literature. This is because the theoretical calculation just considers the 16-bit resolution of the internal calculations in the camera, and ignores the system random noise. In fact, the influence of the system random noise has to be considered in the accurate measurement of small field of view. However, the 10μm resolution of the ProReflex-MCU120 system is sensitive enough for many biomechanical applications, including the measurement of tooth movement, which is the aim of the present study.

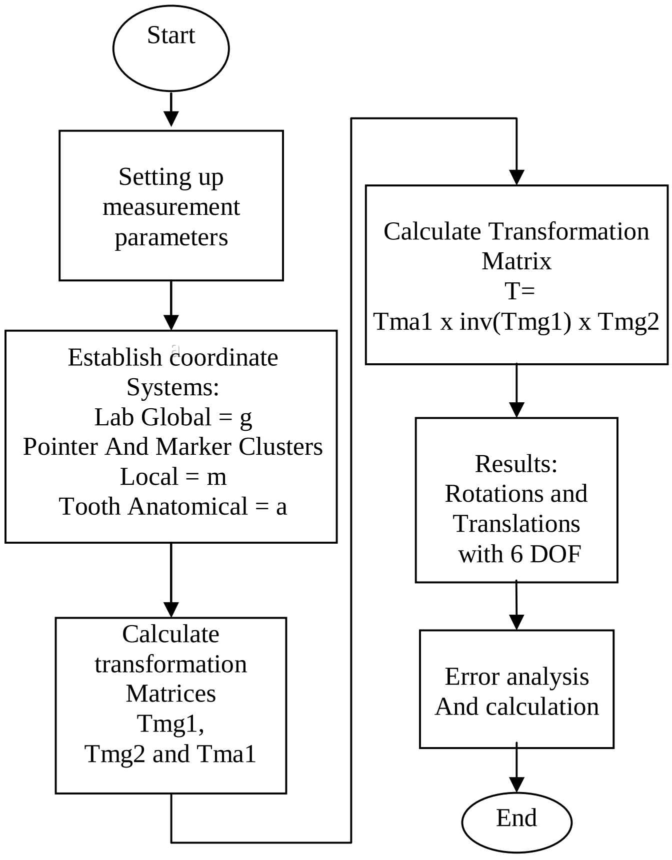


Fig. 4. Block diagram of data processing software.

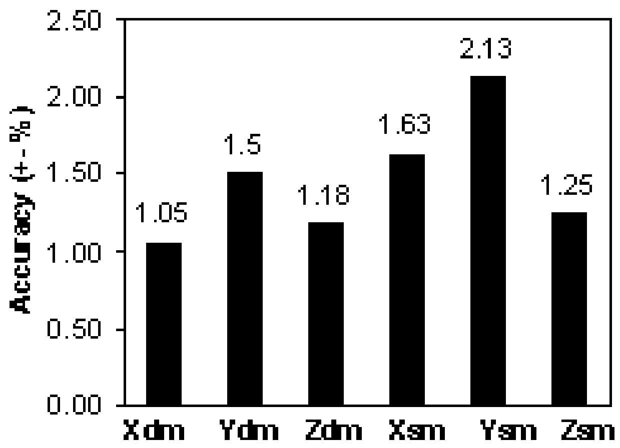


Fig. 5. The system measurement accuracy (±%) in the 20-200μm ranges of x, y, z directions, using diamond markers (dm) and spherical markers (sm). The results were calculated with the percentage of maximum absolute error in the full range divided by the measurement range.

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